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Large Scale Field Trial Results on Time Domain Compression for Uplink Joint Detection

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***Abstract*—Inter-cell interference in the cellular uplink can be combated effectively by joint detection (JD) of multiple users at cooperative base stations, a concept known as network MIMO or more generally as coordinated multi-point (CoMP). Field trials verify large improvements in spectral efficiency and fairness which were proven theoretically. On the downside, JD requires a vast amount of data traffic to be exchanged over the backhaul. However, recent studies promise great performance of JD even under stringent backhaul constraints provided that the exchanged signals are compressed. The present work investigates the limits and potentials of this approach in a practical setting using large scale field trials.**

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 drastically 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 current, most promising proposals, for an improved system setup consider the use of CoMP techniques for the uplink and downlink. Previous field trial publications such as [2], [3] demonstrate that today’s technology is ready to support these concepts. In [4], with a large scale field trial, we show 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, indicating a strong increase of fairness by using cooperation. As a drawback, [4] reports that the backhaul requirements for JD are vast. [5] comes to a similar conclusion based on system level simulations. Theoretical analysis, on the other hand, promises great increases in spectral efficiency even under limited backhaul capacity [6]–[8]. However, these results have to be validated under realistic conditions and because the models investigated are very simple. The performance of multiple scalar and vector compression schemes for uplink JD were evaluated in [9] by assessing the post detection SINR in a small scale field trial. It was shown that scalar compression already achieves a remarkable performance for about $4-5$ bit per real sample. In this correspondence, we continue this observation by presenting large scale field trials of uplink JD where compression of the time domain signal is used in order to reduce the backhaul capacity required.

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, and a summary is given in Section V.

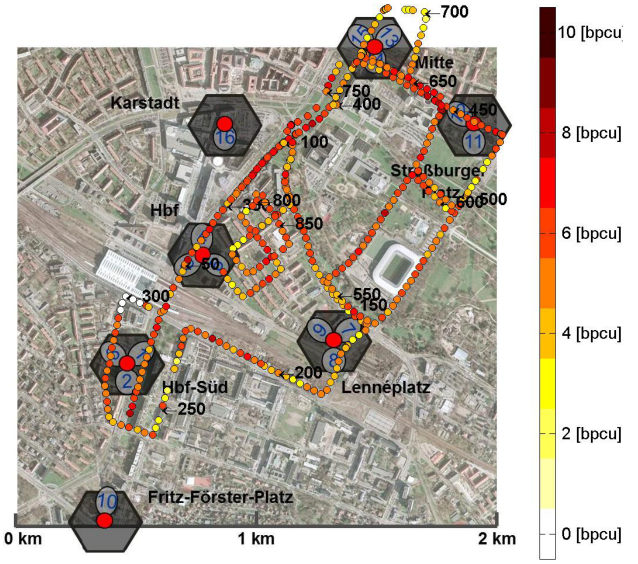

Fig. 1. Field trial setup and measurement trajectory, indicating the sum rate (in bits per channel use) achieved for joint detection of 2 UEs at two cooperation BSs. The maximum compression accuracy is used. Map data © Sandstein Neue Medien GmbH (http://stadtplan.dresden.de)

II. FIELD TRIAL SETUP

Compared to [4], the field trial setup is increased from 12 to 16 BSs deployed at 7 UMTS sites in downtown Dresden, as shown in Figure 1. Synchronization of BSs, which is required for joint detection, is done through GPS fed reference normals. Each BS is equipped with a single antenna (58 degrees half-power beamwidth and 14 dBi gain). The user equipments (UEs) share the same resources in time and frequency. Employing one dipole antenna, they transmit using orthogonal frequency division multiplexing (OFDM) and a sequence of different modulation and coding schemes (MCSs), as listed in Table II. Both are assembled on the same bus for practical reasons. Thus, the UE distance is limited to 5 m. For various additional parameters we refer the reader to Table I. The signals received at all BSss are recorded for

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TABLE I
TRANSMISSION PARAMETERS.

BS distance	350 - 600 m
BS antenna height	30 - 55 m
UE antenna height	1.5 m
Number of antennas per BS	$N_{\text{bs}} = 1$
Carrier frequency	2.53 GHz
System bandwidth	20 MHz
Sampling frequency	$r_{\text{s}} = 30.72$ MHz
Num. physical resource blocks (PRBs)	30
Sub-carriers per PRB	12
UE transmit power	18 dBm
Quantization resolution	12 bit per real sample (bprs)

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

offline evaluation. Thus, the focus of the investigation is on physical layer evaluation.

III. SIGNAL PROCESSING ARCHITECTURE AND EVALUATION CONCEPT

We will now explain, in brief, the general signal processing steps performed in the offline evaluation chain mentioned earlier. For further details we refer the reader to [2].

Synchronization: The carrier frequency of the BS is synchronized by using Global Positioning System (GPS) fed reference normals that have a stability of about 10^{-9}. The frequency offset of the UE is pre-compensated via downlink reference signals. Compared to the sub-carrier spacing, the remaining offset of less than 200 Hz is small enough to be able to disregard 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 symbols. 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 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 $\hat{\mathbf{h}}$. We exploit the auto-correlation properties of $\hat{\mathbf{h}}$ to separate noise and signal components, and compute their respective power. Using this approach, one noise variance $\hat{\sigma}_m^2$ is determined for each BS m. Note that the estimated noise variance possibly includes the effects of compression distortion, as explained later on.

Symbol 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

$$y_m = h_{m,1}x_1 + h_{m,2}x_2 + n_m, \tag{1}$$

where $y_m \in \mathbb{C}$ is the signal received by BS m, $h_{m,k} \in \mathbb{C}$ denotes the channel gain from UE k to BS m, $x_k \in \mathbb{C}$ is a symbol transmitted by UE k, and $n_m \in \mathbb{C}$ denotes additive, uncorrelated noise of variance $\sigma_m^2\mathbf{I}$. The channel vectors include UE transmit power due to the assumption of $E\{x_k x_k^H\} = 1$. The set of BSs that form a cooperation cluster is denoted by $\mathcal{C}$ with elements $\{c_1 \dots c_C\}$, where the cooperation cluster size is denoted by $C = |\mathcal{C}|$. The corresponding transmission model for the cluster is given by

$$\mathbf{y}_{\mathcal{C}} = \begin{bmatrix} h_{c_1,1} & h_{c_1,2} \\ \vdots & \vdots \\ h_{c_C,1} & h_{c_C,2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathbf{n}_{\mathcal{C}}, \tag{2}$$

where $\mathbf{y}_{\mathcal{C}} \in \mathbb{C}^{[C\times 1]}$ are the signals received by the C antennas of the cluster.

The following detection concepts are considered:

- Independent decoding of both UEs by different BSs.
- Both UEs are decoded by the same BS, optionally using successive interference cancellation (SIC).
- $C - 1$ BSs forward their compressed (see following paragraph) received signal to another BS, where both UEs are decoded jointly, either using linear equalization or SIC (JD+SIC).

Please refer to [6] for further information on these schemes and an information theoretic study of their performance.

Detection itself is generally based on the same MMSE filters (possibly using SIC) that were described in [9].

Compression: A major drawback of JD is the large amount of information that needs to be exchanged among BSs, which potentially requires an expensive overhaul of the backhaul infrastructure. Theoretical research on this topic emphasizes the benefits of compression to reduce the backhaul required. However, compression causes a distortion which reduces the throughput of the entire system. To minimize this distortion for a certain backhaul rate, compression is optimized according to the probability distribution of the input signal which changes constantly due to time varying channels. We distinguish two fundamental system choices: compression of the time domain signal or the frequency domain signal. Considering the former, the signal to be compressed and exchanged (in the time domain) is a superposition of multiple (time domain) OFDM samples and AWGN, thus it is assumed to be Gaussian, and since an automatic gain control (AGC) is used before quantization, the statistics of the input signal is assumed to be constant for one measurement. Furthermore, the exchanged signal contains control information which is beneficial because it does not need to be exchanged via a separate channel. For these practical reasons, we use compression of the time domain signal in this field trial evaluation. In particular, we use scalar compression using codebooks that minimize the average

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distance between the original and the compressed samples as found by Lloyd [10] and Max [11]. It was shown in [9] that this form of compression achieves a good trade-off with regard to performance and complexity. For Gaussian signals optimal tables of codebooks are available. More complex algorithms, like vector compression or the use of a Karhunen-Loève transform for the exploitation of antenna correlation, will be considered in future work.

In the setup investigated, one BS functions as the joint decoder, and the other $C-1$ BSs in the cooperation cluster forward their received signal; they function as remote radio heads. The total backhaul requirement is thus

$$R_{\mathrm{bh}}(r_{\mathrm{bh}}) = 2(C-1) r_{\mathrm{s}} N_{\mathrm{bs}} r_{\mathrm{bh}}, \tag{3}$$

where r_{s} is the sample frequency, r_{bh} the backhaul (compression) rate measured in bits per real sample, N_{bs} the number of BS-antennas ($N_{\mathrm{bs}} = 1$ in this field trial), and 2 is the number of real dimensions per sample. As an example, we compute the required backhaul rate for uncompressed JD in our setup. The quantization resolution in the field trial system is 12 bits per real sample. At a sampling rate of 30.72 MHz, for a usable bandwidth of 20 MHz as defined in LTE, this amounts to a total backhaul rate of $R_{\mathrm{bh}} = 737.3$ Mbps.

Compression of frequency domain signals will be considered in future work. It provides several advantages; in particular:

- support of clustering of different BSs on different frequency blocks → suitable for dynamic user grouping.
- frequency domain signal is not oversampled and guard bands do not need to be exchanged.
- no need to exchange empty resource blocks if a cell is not fully loaded.
- reference and data symbols can be exchanged with different accuracies.

On the other hand, compression in the frequency domain is more challenging from an implementation perspective due to frequency dependence of the channel and because the superposition of a few QAM symbols (on a single sub-carrier) is non-Gaussian in our OFDM system. This problem is reduced in the LTE uplink due to DFT precoding in SC-FDMA.

Soft Demodulation and Decoding: After equalization, signal-to-interference-plus-noise ratios (SINRs) are estimated via an error vector magnitude approach, followed by soft demodulation. The demodulator output is fed into an LTE Rel. 8 compliant decoding chain that uses 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 [4], 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. An experience from [4] was that the maximum spectral efficiency of 16QAM was achieved very often (especially if JD was used), therefore we use up to 64QAM with a maximum coderate of 7/8 in this field trial. For each loop through all MCSs, the maximum achievable rate (MCS) is determined — assuming a constant channel for at least the duration of one loop — emulating a perfect (genie) 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. Because the transmitted codeword is known under field trial conditions we are able to use perfect rate adaptation also for SIC receivers, i.e. we are able to determine the MCS providing the highest rate that is successfully decoded either

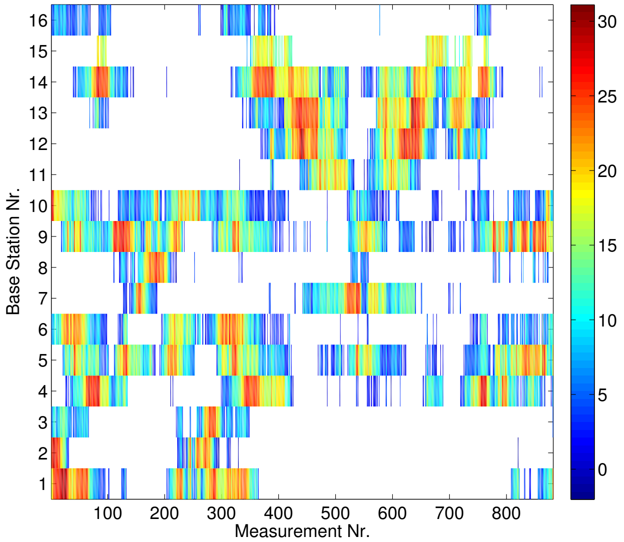

Fig. 2. Average SNR (per measurement) achieved at all BSs of the test bed

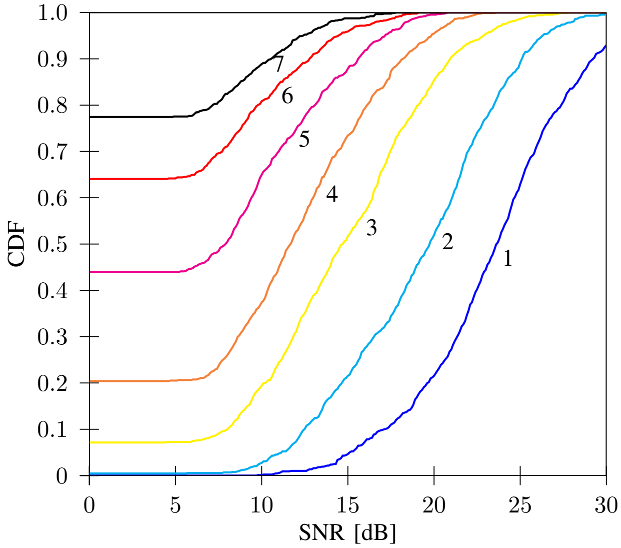

Fig. 3. CDF of minimum SNR that is simultaneously achieved at multiple BSs. The number of BSs that achieve this SNR is denoted next to each plot.

with or without prior SIC and to 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 minimize interference — to a UE that cannot be decoded at all 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 [4], 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 JD of the UEs are determined by a minimum pathloss criterion. In the non-cooperative case, however, each UEs was detected at the BS that achieved the maximum sum-rate. For the SIC case, both UE were detected at the same BS, for linear detection it could be different BSs.

In summary, 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 background interference has been considered.
- 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 as each codeword can be decoded at a different BS even in the non-cooperative case.
- No background interference has been considered and, thus, no interference floor is visible.
- The continuous transmission at maximum power enhances the benefit of SIC because the sum capacity of the multiple access channel is achieved at full transmit power of both UEs.

The sum rate ($r_{\mathrm{sum},p} = r_{1,p}+r_{2,p}$) that was achieved at each measurement position for JD of two BSs (with a maximum compression accuracy of 12 bit per real sample (bprs)) is depicted in Figure 1. We see very high rates especially in the center of the test bed where the UEs can often be effectively detected jointly by two BSs. The SNR that was seen at the BSs at each measurement instance is depicted in Figure 2. In this case, the SNR was determined by taking the ratio of average power on the data sub-carriers and power on empty sub-carriers carry only noise. The signal power is, therefore, the sum power of signals received from both UEs. The result shows that for most measurement positions the UE signals are received with good strength at multiple BSs, a fact that supports the basic motivation for using JD. It is interesting to investigate the channel quality from the UEs to different BSs of the test bed that could potentially form a cooperation cluster. Figure III shows the CDF of the SNR that is simultaneously achieved at an increasing numbers of BSs. For example, we see that the SNR at three different BSs is above 15 dB in about 50 % of the measurements indicating the potential benefit of JD of using more than two BSs. However, a much further increase of the cooperation cluster size is not beneficial because most of the backhaul will be utilized for the exchange of noise, as shown in [7]. This aspect will be addressed in greater detail later in this section.

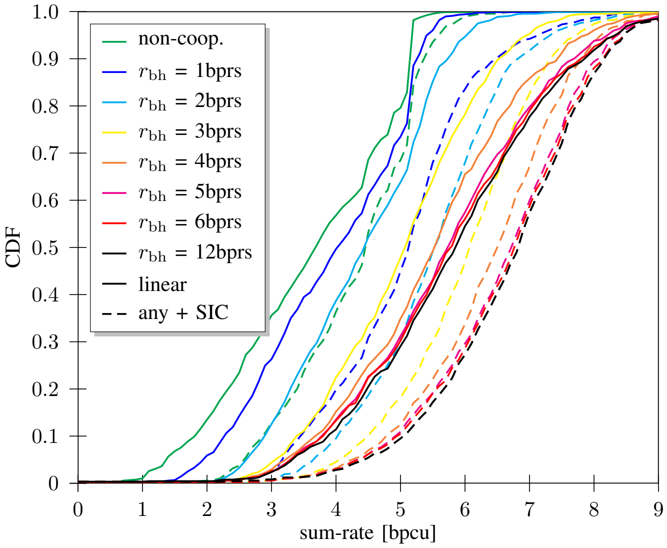

Fig. 4. Sum-rate CDF for non-cooperative detection (left green curve) and JD of two BSs ($C = 2$) at different backhaul (compression) rates. The solid lines are for linear and dashed lines for SIC detectors. The black curve on the right, achieving the best performance, is for JD + SIC.

The CDF of the sum rate for non-cooperative (non-coop.) detection and JD (possibly using SIC for a cluster size of two BSs, using different backhaul rates is shown in Figure IV. Observing the non-cooperative case, we see that the sum rate barely exceeds 5.25 bpcu, the maximum spectral efficiency of the single user case (see Table II, indicating that only a single user would be scheduled which is indeed the case). If JD is used, the users can be separated effectively at the BSs. Thus, they are scheduled on the same resources and the sum-rate increases beyond the single user bound. Obviously, the potential of spatial separation increases with the compression rate — with a maximum of 12 bprs (the resolution of the AD-converter). However, we see that the maximum JD performance is almost achieved for a backhaul rate of 5 bprs. As shown in Figure 5(a), the average sum-rate for a cluster size of $C = 2$ increases almost linearly between 2 and 8 bit per sample ($1-4$ bprs) and saturates for larger backhaul rates. The same observation basically holds for $C = 3$, but the total rate is higher since signals of two BSs are exchanged. Note that the number of BSs in the cooperation cluster were reduced if the number of BSs that achieved an SNR limit of 5 dB was lower than C, leading to a lower sum compression rate which is considered in Figure 5(a). For $C = 3$, this was the case in about 8 % of the measurements as can be seen in Figure III. We see that JD of more than two BSs makes sense only if the available backhaul capacity is very large and, thus, it is

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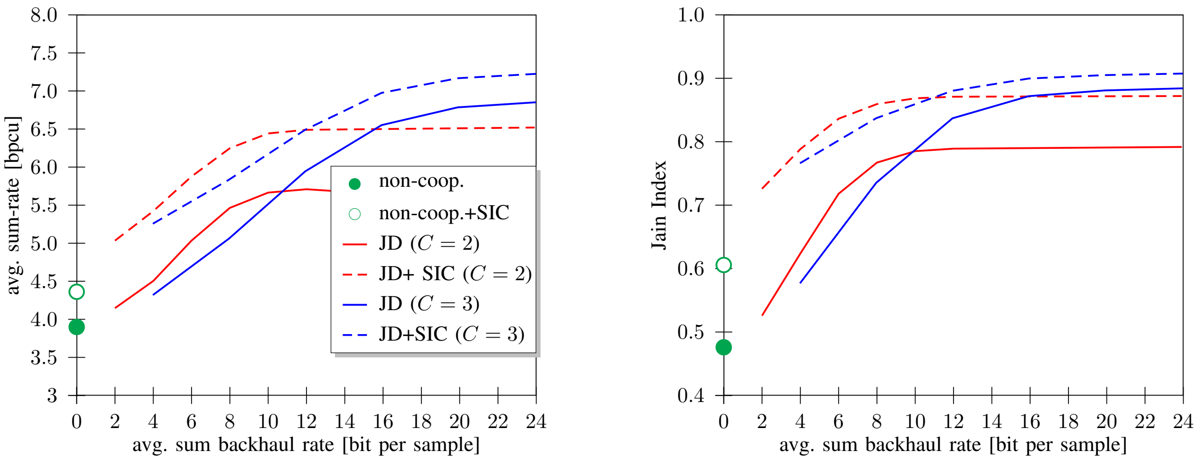

(a) avg. rate over backhaul

(b) Jain index over backhaul

Fig. 5. Avg. sum-rate as of function of the avg. backhaul rate

better to form clusters between only two base stations in the low backhaul regime. Figure 5(a) also shows that the potential benefit of using SIC is large.

It is anticipated that the use of JD (or CoMP in general) leads to greater system fairness. As in [4], we use the Jain index to evaluate this aspect. The Jain index is defined as

$$\text{fairness} = \left(\sum_P \sum_K r_{k,p}\right)^2 \Big/ \left(PK \sum_P \sum_K r_{k,p}^2\right). \qquad (4)$$

Hence, the index reflects the achievable rate distribution of both UEs over the measurement area. (a value of 1 indicates maximum fairness). The Jain index as a function of the backhaul is shown in Figure 5(b). We see that nonlinear detection as well as JD leads to a strong increase of this metric.

V. CONCLUSIONS

In this contribution, we presented field trial results for uplink CoMP. Two UEs were moved through an urban cellular testbed with a total of 16 BSs, a setup which allows the assessment of realistic performance gains that are achievable using CoMP. In particular, we compared conventional non-cooperative detection to cooperative JD, where the backhaul requirements were reduced by using compression of the exchanged time domain signal. The average sum-rate could be increased linearly with the compression rate until a threshold of about 4 bit per real symbol which corresponds to a backhaul rate of about 288 Mbps for the field trial setup investigated.

Open topics for future research are compression in the frequency domain and the consideration of inter- and intra site JD. Furthermore, the field trial setup can be expanded using more UEs either in the cooperation cluster or as additional interferers, including backhaul constraints, we will investigate indoor scenarios, and intend to use field trial results as reference data for improved system level models.

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