Comparative Study of Distributed Consensus-based Estimation Schemes for Small-Cell Networks

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***Abstract*—The dense deployment of small-cells is a promising approach to realize the rate demand in future wireless communication systems. Cooperative processing among distributed radio access points is an interesting approach to achieve the performance of centralized solutions with limited backhaul traffic. In this paper, we investigate cooperative multi-user detection by applying the Distributed Consensus-based Estimation (DiCE) algorithm and two recently proposed modifications of it. The schemes are compared by means of communication overhead and estimation performance.**

I. Introduction

Dense deployment of small-cells is a promising candidate to enable the exponential growth of traffic in 5G mobile networks. Small cells reduce the distance between the radio access points (RAP) and the user terminals (UEs) and allow for reusing the spectrum by neighboring RAPs. In order to cope with the strong interference, multi-cell processing is needed and centralized RAN (C-RAN) utilizing base-band pooling units (BBU) is currently under discussion for joint processing among RAPs [1]. However, the exchange of I/Q samples between RAPs and BBUs requires deployment of fibre links over larger distances, as the BBUs are usually far away from RAPs. To reduce high-capacity, long-distance backhaul (BH) links it would be beneficial to interconnect the RAPs in a geometrical area and perform cooperative processing. In recent publications we proposed the Distributed Consensus-based Estimation (DiCE) algorithm and applied the method for joint multi-user detection by iteratively exchanging local estimates between RAPs [2]. Furthermore, we proposed the RO-DiCE (Reduced Overhead DiCE) [3] and the Fast-DiCE [4] modifications to reduce the communication overhead and to improve the convergence speed. In this paper, we oppose these variants and investigate in particular the required communication overhead and the achieved performance.

II. Distributed Detection Schemes

We consider an uplink scenario consisting of N_{UE} UEs utilizing N_{T} transmit antennas and N_{RAP} RAPs each equipped with N_{R} receive antennas. The receive signal at RAP j is given by $\mathbf{y}_j = \mathbf{H}_j\mathbf{x}+\mathbf{n}_j$ with the stacked transmit vector $\mathbf{x} \in \mathbb{C}^{N_{\text{UE}}N_{\text{T}}}$ [2]. If all RAPs would forward their observations and channel matrices to a central processing node, we could derive the overall MIMO system $\mathbf{y} = \mathbf{H}\mathbf{x}+\mathbf{n}$ with the stacked observation vector $\mathbf{y} \in \mathbb{C}^{N_{\text{RAP}}N_{\text{R}}}$ facilitating central estimation like, e.g., the central Least Squares (LS) problem $\tilde{\mathbf{x}} = \arg \min_{\mathbf{x}'} \|\mathbf{y} - \mathbf{H}\mathbf{x}'\|^2$ achieving the estimate $\tilde{\mathbf{x}}$ based on all observations $\mathbf{y}$.

As an alternative, the authors proposed the DiCE algorithm that solves the LS problem in a distributed fashion [2]. This is facilitated by reformulating the LS problem into a set of optimizations over local variables $\mathbf{x}_j$ per node j with coupling by a consensus constraint $\mathbf{x}_i = \mathbf{x}_j$ for all RAPs $i \in \mathcal{N}_j$ that are directly connected to RAP j via the BH network. By introducing auxiliary variables $\mathbf{z}_j$ per node j, the iterative, distributed solution was derived with update equations in iteration k for every node j [2]:

$$\mathbf{z}_j^k = \frac{\mu}{|\mathcal{N}_j^+|} \sum_{i\in\mathcal{N}_j^+} \left[\tfrac{1}{\mu}\mathbf{x}_i{}^{k-1} - \boldsymbol{\lambda}_{ij}^{k-1}\right] \tag{1a}$$

$$\boldsymbol{\lambda}_{ji}^k = \boldsymbol{\lambda}_{ji}^{k-1} - \tfrac{1}{\mu}\left(\mathbf{x}_j^{k-1} - \mathbf{z}_i^k\right) \qquad \forall i \in \mathcal{N}_j^+ \tag{1b}$$

$$\mathbf{x}_j^k = \left(\mathbf{H}_j^{\text{H}}\mathbf{H}_j + \frac{|\mathcal{N}_j^+|}{\mu}\mathbf{I}_{N_{\text{I}}}\right)^{-1} \cdot \left[\mathbf{H}_j^{\text{H}}\mathbf{y}_j + \sum_{i\in\mathcal{N}_j^+}\left(\frac{\mathbf{z}_i^k}{\mu} + \boldsymbol{\lambda}_{ji}^k\right)\right] \ . \tag{1c}$$

Variables $\mathbf{x}_j^k$ and $\mathbf{z}_j^k$ represent intermediate estimates at node j after iteration k, $\boldsymbol{\lambda}_{ji}^k$ and $\boldsymbol{\lambda}_{ij}^k$ denote Lagrangian multipliers, and set $\mathcal{N}_j^+ = \mathcal{N}_j \cup \{j\}$ contains node j and its neighboring nodes.

In order to accelerate the iterative detection process a prediction step for the auxiliary variables $\mathbf{z}_i^k$ and the Lagrangian $\boldsymbol{\lambda}_{ji}^k$ was introduced for the Fast-DiCE algorithm [4]. To this end, at node j the *predictor* $\tilde{\mathbf{z}}_{ji}^k = \mathbf{z}_i^k + \gamma_k\left(\mathbf{z}_i^k - \mathbf{z}_i^{k-1}\right)$ for the auxiliary variable of node i is calculated and used in (1c). Thus, the newest received estimate $\mathbf{z}_i^k$ is *extended* by the gradient of the auxiliary variable $\mathbf{z}_i^k - \mathbf{z}_i^{k-1}$ weighted by the step size parameter γ_k. Similarly, predictors $\tilde{\boldsymbol{\lambda}}_{ji}^k$ are calculated based on $\boldsymbol{\lambda}_{ji}^k$ and $\boldsymbol{\lambda}_{ji}^{k-1}$ and used in (1a) and (1c). As demonstrated in Section III, fewer iterations are required by Fast-DiCE to achieve the same estimation quality as DiCE leading to a considerable reduction of the communication effort at the expense of a slightly higher computational complexity due to the prediction step.

In order to reduce the communication overhead for exchanging variables among neighboring RAPs, the RO-DiCE applies

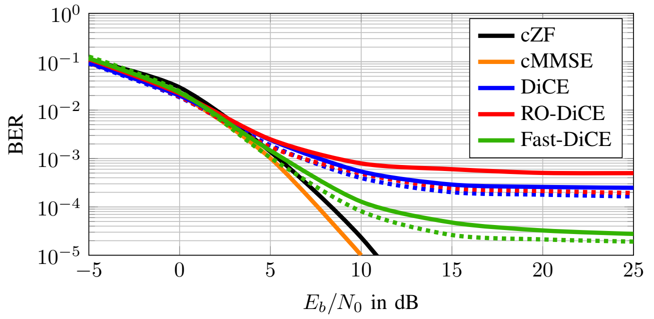

Fig. 1. Average BER over all RAPs with perfect (····) and noisy (—) inter-node links.

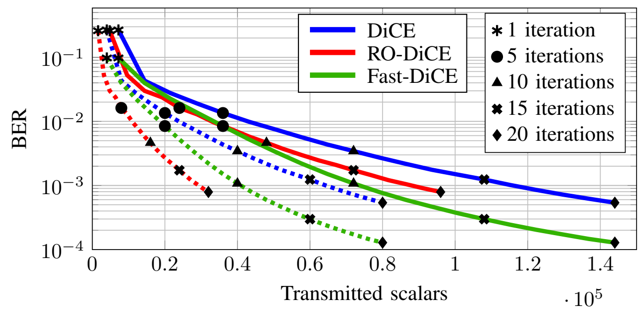

Fig. 2. BER versus communication overhead for P2P (—) and P2MP (····) inter-node links for fixed $E_\mathrm{b}/N_0 = 10$ dB.

in the update equations (1a) and (1c) the approximations [3]

$$\frac{1}{|\mathcal{N}_j^+|}\sum_{i\in\mathcal{N}_j^+}\boldsymbol{\lambda}_{ij}^{k-1} \approx \boldsymbol{\lambda}_{jj}^{k-1} \approx \frac{1}{|\mathcal{N}_j^+|}\sum_{i\in\mathcal{N}_j^+}\boldsymbol{\lambda}_{ji}^{k-1}\,. \tag{2}$$

Thus, the sums of multipliers are approximated by the locally available multiplier $\boldsymbol{\lambda}_{jj}^{k-1}$ which omits the exchange of multipliers among nodes at all.

III. Performance Evaluation

In order to investigate the performance of the different distributed estimation algorithms in a small-cell scenario, Monte-Carlo simulations for a system with $N_\mathrm{RAP} = 4$ RAPs each equipped with $N_\mathrm{R} = 2$ receive antennas serving $N_\mathrm{UE} = 2$ UEs with $N_\mathrm{T} = 2$ transmit antennas have been performed.

Fig. 1 shows the average bit error rate (BER) over all RAPs for uncoded QPSK transmissions over i.i.d. Rayleigh fading channels, where the central ZF and MMSE solutions are shown for reference. Here, a fully meshed BH network is assumed with either perfect or additively disturbed BH links corresponding to $\mathrm{SNR}_\mathrm{BH} = 30\,\mathrm{dB}$. The DiCE algorithms were terminated after $N_\mathrm{It} = 20$ iterations, leading to an error floor, which can be decreased by more iterations. In case of error-free links only a small loss is visible for RO-DiCE due to the introduced approximation (2). However, the loss increases for disturbed BH links as consensus is only achieved in the mean sense. Furthermore, significant improvements are visible for Fast-DiCE due to the applied prediction step.

The information exchange on the links between RAPs comprises variables which need to be made available to all neighbors and variables which are specific to certain neighbors. In case of omnidirectional wireless inter-node communication (point-to-multi-point, P2MP), the broadcast nature allows to transmit the intermediate estimates $\mathbf{z}_j^k$ and $\mathbf{x}_j^k$ conveniently to all neighbors $i \in \mathcal{N}_j$, while the exchange of $\boldsymbol{\lambda}_{ji}^k$ requires dedicated transmissions to each neighbor (unicast). In such a scenario, the RO-DiCE offers significant reductions due to the omitted exchange of multipliers. However, in case of point-to-point (P2P) links between RAPs only unicast transmissions are possible. Thus, for investigating the actual communication overhead the applied BH approach has to be considered.

Fig. 2 shows the average BER versus the total communication overhead assuming the same system configuration as before for a fixed $E_\mathrm{b}/N_0 = 10$ dB and $\mathrm{SNR}_\mathrm{BH} = 30$ dB. Depicted are the results for P2P links and for P2MP links for realizing a logical full-meshed network. The graphs indicate, that Fast-DiCE is able to achieve the same BER compared to DICE or RO-DiCE with fewer iterations, leading to a reduced communication overhead and less computational latency. Comparing P2MP with P2P communications the overhead is significantly reduced since the intermediate estimates $\mathbf{z}_j^k$ and $\mathbf{x}_j^k$ are broadcasted. A further reduction of overhead per iteration is achieved by RO-DiCE which avoids the unicast exchange of Lagrangian $\boldsymbol{\lambda}_{ji}^k$ at all.

IV. Conclusion

For a small-cell network we proposed the Distributed Consensus-based Estimation (DiCE) algorithm for joint multi-user detection. We discussed two DiCE modifications and compared the performance of these schemes by means of error rate and communication overhead. However, as the considered problem is quite general, the presented framework can be applied also for other tasks in distributed systems.

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