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Distributed Iterative Detection With Reduced Message Passing for Networked MIMO Cellular Systems

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***Abstract*—This paper considers base station cooperation (BSC) strategies for the uplink of a multiuser multicell high-frequency reuse scenario where distributed iterative detection (DID) schemes with soft/hard interference cancelation (IC) algorithms are studied. The conventional distributed detection scheme exchanges soft-symbol estimates with all cooperating BSs. Since a large amount of information needs to be shared via the backhaul, the exchange of hard bit information is preferred; however, performance degradation is experienced. In this paper, we consider a reduced message passing (RMP) technique in which each BS generates a detection list with the probabilities for the desired symbol that are sorted according to the calculated probability. The network then selects the best detection candidates from the lists and conveys the index of the constellation symbols (instead of double-precision values) among the cooperating cells. The proposed DID-RMP achieves intercell interference (ICI) suppression with low backhaul traffic overhead compared with the conventional soft bit exchange and outperforms the previously reported hard/soft information exchange algorithms.**

***Index Terms*—Base station cooperation (BSC), distributed iterative detection (DID), iterative (turbo) processing, multiple-input–multiple-output (MIMO), multiuser detection.**

I. INTRODUCTION

The growing demand for mobile multimedia applications requires higher data rates and reliable links between base stations (BSs) and mobile users. The improvement of system capacity can be achieved by introducing higher frequency reuse and microcell planning [1], [2]. In such a network configuration, higher spectral efficiency is obtained; however, the intercell interference (ICI) becomes dominant at the cell edges, particularly in an aggressive frequency reuse scenario [1], [3]. The application of interference mitigation techniques is necessary in these systems to prevent a reduced data rate of the users located at the cell edge and improve system fairness [14], [15].

Strategies to deal with the ICI in the system uplink include joint multiuser detection (JMD) [3], [8], [9], [16] and distributed iterative detection (DID) [5], [7], [12], [18], [19]. In terms of JMD, the BSs for each cell make the received signals available to all cooperating cells. With this setting, the receivers not only use the desired signal energy but also the energy from the interferers leading to a much improved received signal-to-interference-plus-noise ratio (SINR). Both array and diversity gains are obtained, resulting in a substantial increase in system capacity [12]. Despite the optimality of JMD, it needs to exchange all the quantized received signals between the cooperative BSs via a wired or microwave backbone network, which brings about huge background data traffic [2], [5]. To reduce the backhaul traffic, clusters may be applied, a group of BSs can form a cluster, and the JMD can be performed in a central unit. The information is exchanged within the cluster, which reduces the backhaul and the complexity. However, the JMD-based structure has many restrictions: 1) the performance degrades at the boundaries of the clusters; 2) the central units are required to support a large number of users in the cluster that introduces high detection complexity; and 3) it requires transmission of quantized received signals over the wired network to the central unit that causes high backhaul traffic [1], [5].

To circumvent the aforementioned problems, an advanced interference mitigation technique for distributed receivers is introduced. A DID structure is presented as an alternative to JMD for cooperative detection with affordable backhaul traffic between cooperating BSs [4], [5], [12]. With the DID scheme, iterative processing is performed at the network level. The receiver detects each user stream in its corresponding cell and iteratively refines the estimate of the transmitted symbol with the help of the information provided by other cooperating cells. Each BS detects the desired user/stream only, the other interfering signal is canceled or treated as noise [10], [13]. The output of the receiver is used to reconstruct the transmitted symbol, and this estimate is conveyed to the cooperating BSs. Each BS exchanges its estimates with the neighbors, the reconstructed interferers are canceled from the received signal, and the power of the interference reduces as more iterations are performed. With DID, the detection complexity is restricted to the number of data streams inside the cell [5]. Despite their advantages, DID techniques have the drawback that the interference cancelation (IC) is performed at the network level, the exchange of soft information brings about high backhaul traffic, and the iterative detection delay must be minimized.

In the remaining part of this paper, we focus on interference mitigation techniques [7], [14], [15] dealing with the multiuser multicell detection through BS cooperation (BSC) in an uplink interference-limited aggressive frequency reuse scenario. In the proposed DID with reduced message passing (DID-RMP) algorithm, the cooperating BSs exchange information while performing interference mitigation based on single-user or multiuser detection. Instead of exchanging the soft estimates introduced in [5], [10], and [12], the proposed algorithm generates a sorted list containing the probability of the constellation symbols given the channel information. The indexes of the constellation symbols with high probability are exchanged via the backhaul link. A selection unit (SU) is also proposed in the network to provide the best candidates from the list. The indexes are exchanged among the BSs in an iterative manner, and the system improves the estimate of the desired signal with each iteration loop. The indexed interference at the cooperating BSs is subtracted from the received signal, resulting in a reduced interference level and more reliable data estimates. The simulation results indicate that the proposed DID-RMP scheme is able to outperform the soft-symbol cancelation technique reported in [5] and [12] while requiring much less backhaul traffic.

This paper is structured as follows. The system and data model is presented in Section II. In Section III, the iterative detection with RMP is discussed, which also involves soft/hard interference subtraction and the proposed index-based subtraction. The simulation results and the conclusions are presented in Sections IV and V, respectively.

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II. DATA MODEL OF A NETWORKED MULTIPLE-INPUT–MULTIPLE-OUTPUT CELLULAR SYSTEM

We consider an asymmetric multiuser scenario of a networked MIMO cellular system. We assume that the cellular network can detect groups of users that are received by several cooperating BSs [4], [5], [7]. We consider that a number of ϕ cells are grouped into one cluster, that the diversity and array gains can be obtained inside the cluster, and that the interference among the clusters is mitigated through the application of DID schemes. Since we are interested in mitigating the intercluster interference, to simplify our description, we consider the special case $\phi = 1$, where each cell represents a cluster. The scenarios with more cells in the cluster $\phi > 1$ are straightforward.

Let us consider an idealized synchronous uplink single-carrier narrow-band cellular network that aims to capture most of the features of a realistic wireless system with respect to the interference and the need for backhaul. We define M as the number of cooperating BSs and K as the number of users in the cooperating cells, and assume the users and BSs have a single transmit antenna. Extensions to multiple antennas are straightforward and are considered later on. In networked MIMO systems, a limited number of cells can work together in order for the backhaul overhead to be affordable [11]; by increasing the number of cooperating cells, a higher number of interfering links are expected to be dealt with. The increased backhaul traffic is a direct consequence of the BSs dealing with a higher number of interferers. Therefore, the number of cooperating cells should be limited. In this system, the transmitted data of each user are protected by the channel codes separately. A message vector $\boldsymbol{m}_k$ from user k is encoded by a channel code before a bit interleaving operation. The resulting bit sequence $\boldsymbol{b}_k$ has Q entries, and $k = 1, 2, \ldots, K$ are the indexes of the interfering users. The sequence is then divided into groups of J bits each, which are mapped to a complex symbol vector as the output of the user k; this operation is denoted $\boldsymbol{s}_k = [s_{k,1}, \ldots, s_{k,Q_s}] = \text{map}(\boldsymbol{b}_k)$, where $Q_s = Q/J$, and each entry of $\boldsymbol{s}_k$ is taken from a complex constellation $\mathcal{A}$ with power $E\{|s_{k,j}|^2\} = \sigma_s^2$.

A. Data Model for Single-Antenna Users and BSs

A $K \times 1$ symbol vector $\boldsymbol{s}[i] = [s_1[i], s_2[i], \ldots, s_K[i]]^T$ is transmitted simultaneously by all K users. At BS m, the received symbols $r_m[i]$ are given by

$$r_m[i] = \boldsymbol{g}_m[i]\boldsymbol{s}[i] + v_m[i], \qquad 1 \le i \le Q_s \tag{1}$$

where $\boldsymbol{g}_m[i] \in \mathbb{C}^{1\times K}$, $m = 1, \ldots, M$; the entry $[i]$ is the time index; and $v_m[i]$ denotes the additive zero-mean complex Gaussian noise with variance $E\{v[i]v[i]^*\} = \sigma_v^2$.

The entries of the $1 \times K$ row vector $\boldsymbol{g}_m$ are the element-wise product of $h_{m,k}$ and $\sqrt{\rho_{m,k}}$, where $h_{m,k}$ is the complex channel realization from the kth user to the mth BS with independent and identically distributed (i.i.d.) $\mathcal{CN}(0, 1)$. The coefficients $\rho_{m,k}$ reflect the path loss with respect to BS m and user k. Similarly to [5], we separate $r_m[i]$ into four terms expressed by

$$\begin{aligned} r_m[i] &= g_{m,d}s_d[i] + \sum_{n\in\mathcal{C}_m} g_{m,n}s_n[i] + \sum_{n\in\hat{\mathcal{C}}_m} g_{m,o}s_o[i] + v[i], \\ &= \sqrt{\rho_{m,d}}h_{m,d}s_d[i] + \sqrt{\rho_{m,n}}\sum_{n\in\mathcal{C}_m} h_{m,n}s_n[i] \\ &\quad + \sqrt{\rho_{m,o}}\sum_{n\in\hat{\mathcal{C}}_m} h_{m,o}s_o[i] + v[i] \end{aligned} \tag{2}$$

where the first term denotes the desired signal (indexed by $_d$), and the second and third terms denote the strong interference and the weak interference (indexed by $_n$ and $_o$, respectively). Coefficients ρ_n and ρ_o characterize the channel gains with strong and weak interferers, respectively. The set of indexes of all strongly received interference at BS m is denoted $\mathcal{C}_m$ and the weakly received interference is denoted $\hat{\mathcal{C}}_m$.

It is shown in [4] and [5] that the strongest interferers dominate the total ICI. In this model, we constrain the number of strongly received signals to $m_n \le 5$. For example, in a system with $K = M = 4$, the number of strong interferers $\zeta = 2$, the weak interference $\rho_{m,o}$ is equal to zero, and the desired user is denoted $\rho_{m,d} = 1$; then, the coupling matrix is formed as

$$\boldsymbol{P} = \begin{bmatrix} 1 & \rho_{m,n} & \rho_{m,n} & 0 \\ 0 & 1 & \rho_{m,n} & \rho_{m,n} \\ \rho_{m,n} & 0 & 1 & \rho_{m,n} \\ \rho_{m,n} & \rho_{m,n} & 0 & 1 \end{bmatrix}. \tag{3}$$

The coupling matrix $\boldsymbol{P}$ is introduced to describe the configuration of an interference model of a multiuser multicell system. Its diagonal values indicate the power of the link between the BS and the user within the local cell. The off-diagonal values denote the power of interfering links between the BS and the interfering users from other cells. The channel realization of the whole cooperative system $\boldsymbol{G}$ is obtained by the element-wise product of $\boldsymbol{P}$ and $\boldsymbol{H}$ with the elements $h_{m,k}$ following i.i.d. $\mathcal{CN}(0, 1)$.

In this configuration, we assume the BSs have the ability to know from which cells the interfering signals are coming. The BS in the desired cell then notifies the BS of the interfering cells and obtains the estimated transmit signal from that cell to perform IC. The exchanged interfering information is transmitted via a wired backhaul that connects all the BSs in the network.

The SNR is defined as the ratio of the desired signal power at the receiver side and the noise power, which is mathematically described as $\text{SNR}_d := 10\log_{10}(E\{\|h_{m,d}s_d\|^2\})/E\{\sigma_v^2\}$. Let us also denote the average signal-to-interference ratio (SIR) of the desired user k as follows:

$$\text{SIR}_d := 10\log_{10} \times \frac{E\{\|g_{m,d}s_d\|^2\}}{\sum_{n\in\mathcal{C}_m} E\{\|g_{m,n}s_n\|^2\} + \sum_{n\in\hat{\mathcal{C}}_l} E\{\|g_{m,o}s_o\|^2\}}. \tag{4}$$

B. Data Model for Multiple-Antenna Users and BSs

Here, a data model for networked MIMO systems in which the users and BSs are equipped with multiple antennas is discussed. The scalar $r_m[i]$ and vector $\boldsymbol{g}_m[i]$ in (1) are now described in the vector $\boldsymbol{r}_m[i]$ and matrix $\boldsymbol{G}_m[i]$ forms, respectively, as given by

$$\boldsymbol{r}_m[i] = \boldsymbol{G}_m\boldsymbol{z}[i] + \boldsymbol{v}_m[i] \tag{5}$$

where $\boldsymbol{r}_m \in \mathbb{C}^{N_R\times 1}$ is the received vector for the mth BS, and $\boldsymbol{G}_m \in \mathbb{C}^{N_R\times KN_T}$ is the combined channel matrix with $\boldsymbol{G}_m = [\boldsymbol{G}_{m,1}, \ldots, \boldsymbol{G}_{m,k}, \ldots, \boldsymbol{G}_{m,K}]$, where $\boldsymbol{G}_{m,k} \in \mathbb{C}^{N_R\times N_T}$ denotes the channel between user k and BS m. Note that each user has N_T transmit antennas, and each BS has N_R receive antennas. The quantity $\boldsymbol{z} \in \mathbb{C}^{KN_T\times 1}$ is the collection of the data streams from the K users $\boldsymbol{z} = [\boldsymbol{s}_1^T, \ldots, \boldsymbol{s}_K^T]^T$ and $\boldsymbol{s}_k \in \mathbb{C}^{N_T\times 1}$. Equation (2) can be rewritten as

$$\begin{aligned} \boldsymbol{r}_m[i] &= \boldsymbol{G}_{m,d}\boldsymbol{s}_d[i] + \sum_{n\in\mathcal{C}_m} \boldsymbol{G}_{m,n}\boldsymbol{s}_n[i] + \sum_{n\in\hat{\mathcal{C}}_m} \boldsymbol{G}_{m,o}s_o[i] + \boldsymbol{v}_m[i], \\ &= \sqrt{\rho_{m,d}}\boldsymbol{H}_{m,d}\boldsymbol{s}_d[i] + \sqrt{\rho_{m,n}}\sum_{n\in\mathcal{C}_m} \boldsymbol{H}_{m,n}\boldsymbol{s}_n[i] \\ &\quad + \sqrt{\rho_{m,o}}\sum_{n\in\hat{\mathcal{C}}_m} \boldsymbol{H}_{m,o}\boldsymbol{s}_o[i] + \boldsymbol{v}_m[i] \end{aligned} \tag{6}$$

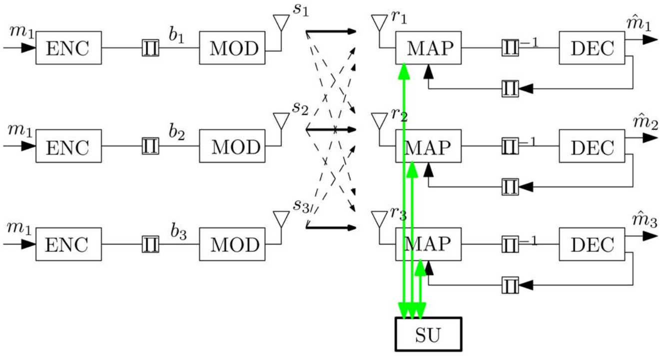

Fig. 1. Example configuration showing a cooperating three-cell network. The dashed lines between the transmitter and the receiver denote the ICI, whereas the solid lines denote the desired signal.

where we assume that the N_T antennas for each user have the same channel gain coefficients ρ_n and ρ_o. The coupling matrix given in (3) and the definition of SNR and SIR can be generalized accordingly.

To simplify the description of the proposed structure and its traditional counterparts, we first employ the single-antenna case $N_T = N_R = 1$ in the following.

III. DISTRIBUTED ITERATIVE DETECTION WITH REDUCED MESSAGE PASSING

Here, the decision-aided DID structure is described in detail. Earlier, the distributed iterative signal processing in an interference-limited cellular network is reviewed. In the following, the soft and hard parallel IC algorithms are based on the quantized estimates from the cooperating BSs. The end of this section is devoted to the description of the proposed DID-RMP.

A. *Decision-Aided Distributed Iterative Detection*

The setup for performing the distributed detection with the information exchange between BSs is shown in Fig. 1. The K users' data are separately coded and modulated to complex symbols after bit interleaving. At each BS, the received signal $r_m[i]$ is the collection of the transmitted signal and the Gaussian noise.

In addition, each BS equips a communication interface for exchanging information with the cooperating BSs. The information is in the form of a bit sequence that represents the quantized soft estimates. The interface is capable of transmitting and receiving information. Via these interfaces, each cooperating BS is connected to a device, namely the SU, and is ready to receive and transmit the information for cooperation. The proposed SU has very limited computational power and it can be integrated with BSs in the network.

In each BS, a block of received signals $r_m[i]$ is used by the maximum *a posteriori* (MAP) demapper to compute the *a posteriori* probability in the form of log-likelihood ratios (LLRs), which are given by

$$\Lambda_1^p\left[b_{j,k}[i]\right] = \log \frac{P\left[b_{j,k}[i] = +1 | r_m[i]\right]}{P\left[b_{j,k}[i] = -1 | r_m[i]\right]} \tag{7}$$

where the equation can be solved by using Bayes' theorem, and we leave the details to [10] and [13]. The detector and the decoder are serially concatenated to form a "turbo" structure, the *extrinsic* information is exchanged by the two soft-input–soft-output components. We denote the *intrinsic* information provided by the decoder as $\Lambda_2^p[b_{j,k}[i]]$, and the bit probability is $P[b_{j,k}[i]] = \log(P[b_{j,k}[i] = +1])/(P[b_{j,k}[i] = -1])$. From [10], the bitwise probability is obtained by

$$\begin{aligned} P\left[b_{j,k}[i] = \bar{b}_j\right] &= \frac{\exp\left(\bar{b}_j \Lambda_2^p\left[b_{j,k}[i]\right]\right)}{1 + \exp\left(\bar{b}_j \Lambda_2^p\left[b_{j,k}[i]\right]\right)} \\ &= \frac{1}{2}\left[1 + \bar{b}_j \tanh\left(\frac{1}{2}\Lambda_2^p\left[b_{j,k}[i]\right]\right)\right] \end{aligned} \tag{8}$$

where $\bar{b}_j = \{+1, -1\}$. Let us simplify the notation $P[s_k[i]] := P[s_k[i] = c_q]$, where c_q is an element chosen from the constellation $\mathcal{A} = \{c_1, \ldots, c_q, \ldots, c_A\}$. The symbol probability $P[s_k[i]]$ is obtained from the corresponding bitwise probability, and assuming the bits are statistically independent, we have

$$\begin{aligned} P\left[s_k[i]\right] &= \prod_{j=1}^{J} P\left[b_{j,k}[i] = \bar{b}_j\right] \\ &= \frac{1}{2^J}\prod_{j=1}^{J}\left[1 + \bar{b}_j \tanh\left(\frac{1}{2}\Lambda_2^p\left[b_{j,k}[i]\right]\right)\right]. \end{aligned} \tag{9}$$

From (8) and (9), we can easily conclude that $\sum_{|\mathcal{A}|} P[s_k[i]] = 1$. The symbol likelihood $P[s_k[i]]$ can be used to evaluate the reliability of the recovered symbol. A higher probability of detection of $s_k[i]$ can be associated with a higher reliability of estimation of that symbol.

B. *Soft Interference Cancelation*

The soft IC has first been reported in an iterative multiuser code-division multiple-access (CDMA) systems in [10] and later extended by several works [4], [13], [19]. In the algorithm [4], the soft replicas of ICI are constructed and subtracted from the received signal vector as

$$\tilde{r}_{m,k}[i] = r_m[i] - \boldsymbol{g}_m \tilde{\boldsymbol{u}}_k[i] \tag{10}$$

and the replica of the transmitted symbol vector $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{K\times 1}$ is obtained as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{s}_1[i], \ldots, \tilde{s}_{k-1}[i], 0, \tilde{s}_{k+1}[i], \ldots, \tilde{s}_K[i]\right]^T \tag{11}$$

where the estimates of $s_k[i]$ are calculated as

$$\tilde{s}_k[i] = E\left\{s_k[i]\right\} = \sum_{c_q \in \mathcal{A}} c_q P\left[s_k[i] = c_q\right]. \tag{12}$$

The first-order and second-order statistics of the symbols are obtained from the symbol *a priori* probabilities as $\sigma^2_{\text{eff}} = \text{var}\{s_k[i]\} = E\{|s_k[i]|^2\} - |\tilde{s}_k[i]|^2$ and $E\{|s_k[i]|^2\} = \sum_{c_q\in\mathcal{A}} |c_q|^2 P[s_k[i] = c_q]$.

In the case that the users and BSs are equipped with multiple antennas, then (10) can be reformulated as

$$\tilde{\boldsymbol{r}}_{m,k}[i] = \boldsymbol{r}_m[i] - \boldsymbol{G}_m \tilde{\boldsymbol{u}}_k[i]. \tag{13}$$

The soft IC procedure can be considered in two cases. In the first case, the cancelation is performed in terms of users rather than data streams, and we name this case as user-based cancelation. In this case, the interfering signals received from other cell users are canceled, but the interference between the antenna data streams of the desired user remains. Mathematically, the replica of the transmitted symbol vector $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{KN_T\times 1}$ is defined as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{\boldsymbol{s}}_1^T[i], \ldots, \tilde{\boldsymbol{s}}_{k-1}^T[i], 0, \tilde{\boldsymbol{s}}_{k+1}^T[i], \ldots, \tilde{\boldsymbol{s}}_K^T[i]\right]^T \tag{14}$$

where $0 \in \mathbb{Z}^{N_T \times 1}$ and $\tilde{\boldsymbol{s}}^T_{\kappa \neq k}[i], \kappa = 1, \ldots, K \in \mathbb{C}^{N_T \times 1}$. The remaining signal after the IC is the combination of all the data streams transmitted from user k and the noise.

In the second case, we consider each independent antenna data stream received by the BSs, and disregarding which users send them; we name this case as data-stream-based cancelation. In this case, the BSs consider interference in terms of streams instead of users. In a mathematical point of view, the replica of the transmitted signal for stream-based IC $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{KN_T \times 1}$ is defined as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{\boldsymbol{s}}_1^T[i], \ldots, \tilde{\boldsymbol{s}}_{k-1}^T[i], \tilde{\boldsymbol{s}}_k'^T[i], \tilde{\boldsymbol{s}}_{k+1}^T[i], \ldots, \tilde{\boldsymbol{s}}_K^T[i]\right] \quad (15)$$

where the entry $\tilde{\boldsymbol{s}}_k'$ is obtained as $\tilde{\boldsymbol{s}}_k'^T[i] = [\tilde{s}_1[i], \ldots, \tilde{s}_{n_t-1}[i], 0, \tilde{s}_{n_t+1}[i], \ldots, \tilde{s}_{N_T}[i]]^T$. By using this scheme, all the interfering streams are removed after the cancelation procedure.

This soft-interference-cancelation-based algorithm generally outperforms hard IC since it considers the reliability of the cancelation procedure. However, the performance heavily depends on the quantization level. Exchanging the quantized soft bits or LLRs convey reliability information among BSs and involves a large amount of backhaul data per cell per iteration, which make soft IC unattractive.

C. Hard Interference Cancelation

With the hard IC, the estimates of the interfering symbols are the constellation symbols. In this case, the quantization is performed for each estimated symbol. Equation (11) is rewritten as

$$\begin{aligned}\hat{\boldsymbol{u}}_k[i] = [&Q\left(\tilde{s}_1[i]\right), \ldots, Q\left(\tilde{s}_{k-1}[i]\right), 0,\\ &Q\left(\tilde{s}_{k+1}[i]\right), \ldots, Q\left(\tilde{s}_K[i]\right)]^T\end{aligned} \quad (16)$$

where $Q(\cdot)$ is the slicing function that depends on the constellation adopted. The constellation indexes are exchanged among the cooperating BSs. Since no reliability information is included, the cooperation procedure requires significantly less backhaul traffic as compared with the soft interference procedure. All the detected information symbols are exchanged in the initial iteration, and in the subsequent iterations, only the symbols with the constituent bits that have flipped between the iterations are exchanged. The indexed constellation symbols are reconstructed at the neighboring BSs and subtracted from the received signal, the residual noise is considered equal to zero, and $\sigma^2_{\mathrm{eff}} = \sigma^2_v$. In the hard IC configuration, the backhaul traffic can be further brought down by introducing a reliability check of the symbols and by exchanging reliable symbols. It is worth mentioning that, by introducing the reliability check, the error propagation effect can be effectively mitigated. The selected unreliable estimates can be either refined or excluded from the IC procedure. The performance improvement over the hard IC scheme is investigated in [6].

D. Distributed Iterative Detection With Reduced Message Passing

The hard IC is performed in a way that the effect of all the detected symbols, but the intended one, are removed from the received signal. It ignores the reliability of the estimated symbols used for IC, but ignoring the reliability may lead to error propagation, which can significantly deteriorate the performance. The soft IC is then introduced to combat error propagation by using quantized soft symbols; however, this procedure requires more iterations to obtain a good performance that increases the detection delay. In addition, the sharing of quantized symbol estimates requires a higher bandwidth across the network, and the bitwise quantization for every symbol brings about higher complexity. In the following, we present a method that is able to address these problems and keep a low backhaul requirement.

By organizing the probabilities obtained by (9) in decreasing order of values, a list of tentative decisions of $s_k[i]$ is obtained in each BS, as given by

$$\mathcal{L}_k[i] \triangleq \{c_1,\, c_2, \ldots,\, c_\tau\}_k \quad (17)$$

where the number of candidates is $1 \leq \tau \leq |\mathcal{A}|$. Probabilities $\Pr[c_1] \geq \Pr[c_2] \geq \cdots \Pr[c_\tau]$, where $\Pr[c_q] \triangleq P[s_k[i] = c_q | r_m]$ is the probability of the transmitted signal is c_q given r_m. For the simplicity of computation, we only keep candidates with probability higher than a threshold such as $P[s_k[i]] \geq \rho_{\mathrm{th}}$ from the list. Threshold ρ_{th} may be fixed or varied in terms of SINR. It is also worth mentioning that failing to optimize the threshold ρ_{th} would result in either heavy backhaul traffic (ρ_{th} too low) or unacceptable performance (ρ_{th} too high). The optimization of ρ_{th} can be performed by maximizing the SINR of the data streams with the constraint of the maximum allowable backhaul traffic.

For symbols transmitted by each user, we generate a tentative decision list $\mathcal{L}_k$. By listing all the combinations of the elements across K users, a length Γ tentative decision list is formed at the corresponding SU. Each column vector on the list denotes a possible symbol vector $\boldsymbol{s}'_l$, where $l = 1, \ldots, \Gamma$. The size of the list is obtained by

$$\Gamma = \prod_{k=1}^{K} |\mathcal{L}_k|, \quad 1 \leq \Gamma \ll |\mathcal{A}|^K \quad (18)$$

where $|\cdot|$ denotes cardinality. To obtain an improved performance, the maximum-likelihood (ML) rule can be used to select the best among the Γ candidate symbol vectors. Note that, without a designated threshold, an ML search over the whole vector space $\Gamma = |\mathcal{A}|^K$ is performed, which is equivalent to joint ML detection and provides a full diversity order with prohibitive backhaul requirements and detection complexity. However, the DID-RMP algorithm obtains a higher diversity order than that of "perfect IC" with a much smaller candidate list (compared with ML) due to the threshold ρ_{th} and its effective selection of candidates.

The threshold value should be adequately set to generate an affordable list size Γ. The ML criterion, which is equivalent to the minimum Euclidean distance criterion, computes the ML solution as given by

$$\boldsymbol{s}'_{\mathrm{ML}} = \arg \min_{l=1,\ldots,\Gamma} \|\boldsymbol{r}[i] - \boldsymbol{G}\boldsymbol{s}'_l[i]\|^2 \quad (19)$$

where $\boldsymbol{r}[i] = [r_1[i], \ldots, r_m[i], \ldots, r_M[i]]^T$, and $\boldsymbol{G} = [\boldsymbol{g}_1^T, \ldots, \boldsymbol{g}_m^T, \ldots, \boldsymbol{g}_M^T]^T$ are received signals and the user channels for all cooperating cells.

In the given expression, the knowledge of $\boldsymbol{g}_m$ and the received signal $r_m[i]$ for each cell is required to be passed to the SU, which may lead to high backhaul traffic. Additionally, as a central point, there is high computational power demand for the SU to choose the best candidate from the list. To circumvent the aforementioned problems, we introduce the method of RMP that is able to distribute the normalization operations to each cooperating BSs.

Distributed Selection Algorithm: The Euclidean distance $\boldsymbol{d} = \boldsymbol{r}[i] - \boldsymbol{G}\boldsymbol{s}'_l[i]$ in (19) is obtained by

$$\|\boldsymbol{d}\| \triangleq \sqrt{|d_{1,\,m}|^2 + \cdots + |d_{k,\,m}|^2} \quad (20)$$

where $d_{k,\,m} = r_m[i] - \boldsymbol{g}_m \boldsymbol{s}'_l[i]$, $\boldsymbol{g}_m[i] \in \mathbb{C}^{1 \times K}$, $m = 1, \ldots, M$, and $\boldsymbol{s}'_l[i] \in \mathbb{C}^{K \times 1}$. For each BS, we separately calculate the minimum partial weights by

$$l_m^{\min} = \arg \min_{l} |r_m[i] - \boldsymbol{g}_m \boldsymbol{s}'_l[i]|^2. \quad (21)$$

The channel information $\boldsymbol{g}_m$ is known to the local BS m, the candidate with the minimum Euclidean distance index $l_m^{\min}$ is obtained by the SU

TABLE I
ALGORITHM 1: DID-RMP ALGORITHM

Algorithm 1 DID-RMP Algorithm

```
**Initialization** $r_m$, $\boldsymbol{g}_m$, $\Lambda_2^p[b_{j,k}[i]] \leftarrow \mathbf{0}$, $TI$.
**for** $k \leftarrow 1,\ldots,K$ {user k} **do**
    $m \leftarrow k$
    **for** $j \leftarrow 1,\ldots,J$ {bit-mapping} **do**
        $P[b_{j,k}[i]=\bar{b}_j] \leftarrow \frac{1}{2}\left[1+\bar{b}_j\tanh\left(\frac{1}{2}\Lambda_2^p[b_{j,k}[i]]\right)\right]$
    **end for**
    $P\big[s_k[i]\big] \leftarrow \prod_{j=1}^{J} P[b_{j,k}[i]=\bar{b}_j]$
    $\mathcal{L}_k[i] \triangleq \{c_1,c_2,\ldots,c_\tau\}_k$ {candidate list}
    **SU** $\Leftarrow 1,\ldots,\tau$ {index sharing}
    $\boldsymbol{s}'_l[i] \Leftarrow$ **SU** {index fetching}
    $l_m^{\min} \leftarrow \arg\min_l |r_m[i]-\boldsymbol{g}_m\boldsymbol{s}'_l[i]|^2$
    $\tilde{r}_k[i] = r_k[i]-\boldsymbol{h}_k\tilde{\boldsymbol{u}}_k^{\mathrm{ML}}[i]$ {interference cancellation}
    **for** $lo \leftarrow TI$ {turbo iterations} **do**
        $\Lambda_1^p[b_{j,k}[i]] \leftarrow$ interleaving aprior, MAP detection
        $\Lambda_2^p[b_{j,k}[i]] \leftarrow$ deinterleaving aprior, max-log-MAP decoding
    **end for**
**end for**
Decision of systematic bit is obtained via sign$\{\Lambda_2^p[b_{j,k}[i]]\}$
```

via backhaul, and an enhanced detection is obtained. In each iteration, the received signal is subtracted by

$$\tilde{r}_k[i] = r_k[i] - \boldsymbol{h}_k\tilde{\boldsymbol{u}}_k^{\mathrm{ML}}[i] \tag{22}$$

where the selected candidate $\tilde{\boldsymbol{u}}_k^{\mathrm{ML}}$ consists of

$$\tilde{\boldsymbol{u}}^{\mathrm{ML}} = \left[\tilde{s}_1^{\mathrm{ML}},\ldots,\tilde{s}_{k-1}^{\mathrm{ML}},0,\tilde{s}_{k+1}^{\mathrm{ML}},\ldots,\tilde{s}_K^{\mathrm{ML}}\right]. \tag{23}$$

With this multiple candidate structure, an enhanced ICI suppression is obtained. The indexes of the symbols on the tentative decision list $\mathcal{A}_k$ are propagated among the neighboring BSs that require reduced backhaul traffic compared with that of the soft signal cancelation algorithm. Additionally, as more cancelation iterations are performed, the size of the list reduces as the recovered bits are more reliable. This further decreases the backhaul traffic with the following iterations, which is not the case with the approach that adopts a soft IC strategy. We can translate the proposed DID-RMP algorithm as follows. In a cooperative network serving several users, if one estimate is not reliable enough to perform IC, the system uses the side information (symbol indexes) provided by other cooperative cells to refine this estimate; therefore, a more reliable IC in the network level is obtained. The algorithm of the proposed DID-RMP method is summarized in Table I.

For an IC-based method, the performance is bounded by the bit error rate (BER) of isolated cells, the single BS in each cell can only provide a diversity order of one. On the other hand, in an extreme case, if the algorithm searches the whole vector space $\Gamma = |\mathcal{A}|^K$, a full diversity order is obtained, and the optimal detection requires exponentially increased complexity. The DID-RMP algorithm however provides a tradeoff between complexity/backhaul and performance by varying the threshold ρ_{th}, and a higher diversity order is obtained with a short candidate list due to its effective selection of candidates.

IV. COMPLEXITY AND BACKHAUL ANALYSIS

A. *Complexity*

In terms of the complexity, a network-wide parallel IC is adopted to remove the cochannel interference by removing the estimates of the interfering symbols based on the *a priori* LLRs obtained from the single-input–single-output channel decoder. For each IC iteration, the reconstruction operations (8) and (9) require $\mathcal{O}(2J)$ real-valued multiplications. These symbol estimates are used to cancel interference in the receiver vector/scalar (22), which require $\mathcal{O}(K-1)$ complex multiplications. The remaining term is then detected by a soft output MAP detector; the computation of per-stream *a posteriori* LLRs requires $\mathcal{O}(J)$ real-valued multiplication and $\mathcal{O}(3JK)$ complex multiplications, where J is the modulation level that denotes the number constituent bits per symbol, and K is the total number of users for detection.

Unlike a centralized methods that requires $\mathcal{O}(J^K)$ complex multiplications or $\mathcal{O}(K^2(MK))$ operations for the filter-based signal processing [14]–[16], in the proposed DID-RMP structure, each BS separately calculates the minimum partial weights in each cell (21) at the cost of only $\mathcal{O}(\Gamma K)$ complex multiplications and send the constellation indexes to the SU. Therefore, the SU is used as memory storage of constellation indexes with no computational requirement. The proposed SU is incorporated to minimize the computational requirement for the SU and maximize the overall performance across the cells.

To reduce the detection complexity of the proposed DID-RMP algorithm, list sphere decoders [13] and their variants can be used to generate this candidate list with much lower complexity as compared with the optimal ML detector. Furthermore, the MMSE/zero-forcing (MMSE/ZF)-based nonlinear detectors can be used to perform iterative detection as well. The detector first separates the spatially multiplexed data streams and converts the MMSE estimates into bit-level LLRs; then, the procedure of (17)–(19) can be applied. However, for MMSE/ZF-based methods, by fixing an allowable backhaul traffic, a worse BER performance is expected due to its suboptimal performance. To address this, the authors suggest an upgraded version of the successive IC algorithm called multiple-feedback successive interference cancelation [6] to detect the symbols. This algorithm considers the reliability of estimated symbols and refine those unreliable ones. Since this algorithm has a near ML performance with low complexity, we expect a similar performance with the ML-based decoder introduced here.

B. *Backhaul Requirement*

The backhaul requirement for a conventional cooperating cellular system with soft information exchange depends on the resolution of quantization for channel state information, the resolution of quantization for the signal received from each antennas, the number of cooperating BSs, and the number of strong interferers at the receiver side. Whenever a hard information exchange is adopted, the backhaul requirement is significantly reduced with the sacrifice of the detection performance. By calculating the minimum partial weights and exchanging the indexes of candidate symbols, DID-RMP introduces a tradeoff between backhaul requirement and performance.

Fig. 2 shows the backhaul traffic as a function of the number of strong interferers ζ. As QPSK modulation is used, two bits are required to index the constellation symbols to perform hard IC. In practical joint and distributed cooperative networks, the data compression techniques are useful for transmitting the soft-quantized symbols. For fairness, we compare both three and six bits per dimension for quantizing the soft symbol; the data compression is only considered in this section but not in the BER simulations in the following. With the DID-RMP algorithm, the list size Γ does not grow exponentially with the increase in the modulation level (e.g., from QPSK to 16-QAM), but a higher backhaul requirement is expected due to an increasing number of unreliable estimates. On the other hand, if the backhaul reaches its

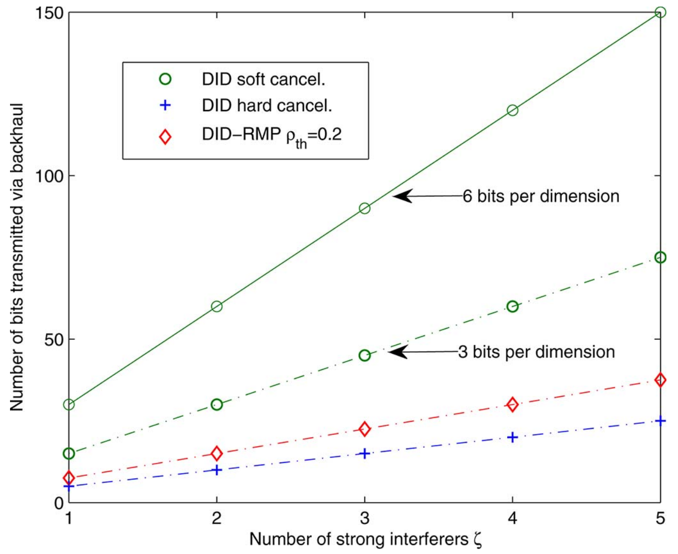

Fig. 2. Number of bits exchanged per symbol detection in a nine-cell network. The number of bits required via backhaul increases with the number of strong interfering links within the cooperative network.

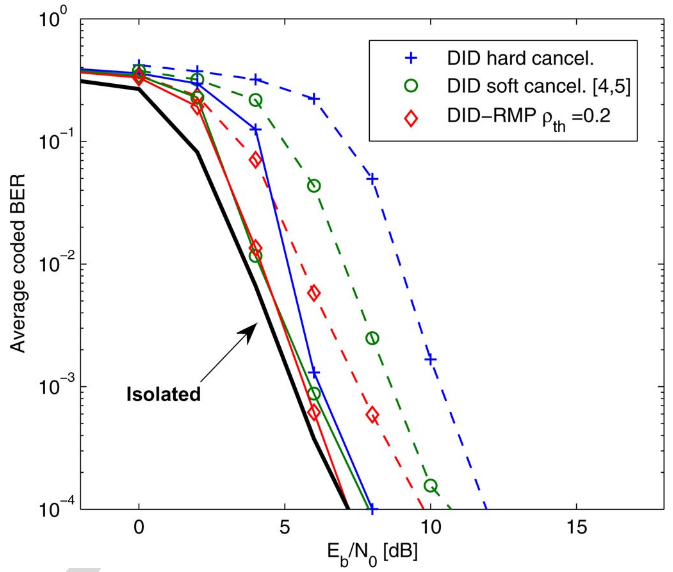

Fig. 3. SNR versus average BER. The solid lines denote a cooperating four-cell network with $\zeta = 2$ strong interferers per cell. The dashed lines denote a cooperating network with nine cells with $\zeta = 3$ strong interferers per cell. The DID soft cancelation is performed according to [4] and [5].

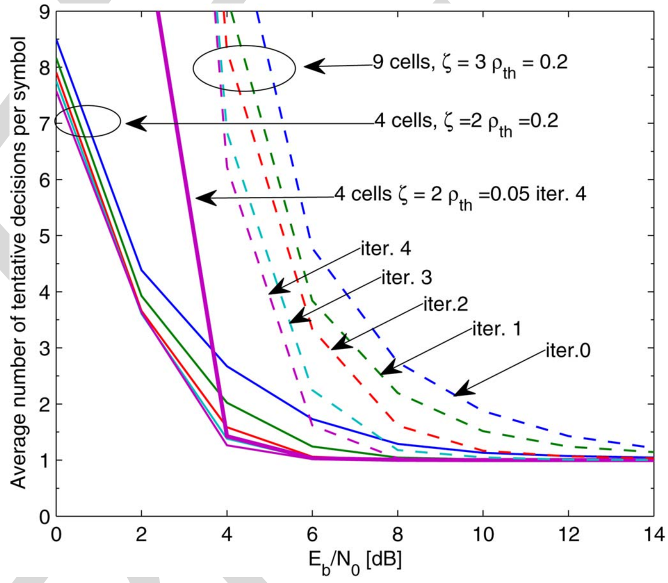

Fig. 4. Number of tentative decisions Γ decreases as the SNR increases. With a smaller threshold ρ_{th} selected, more decision candidates are generated, particularly in the low SNR region.

maximum allowable traffic, performance degradation is also expected. The plots indicate that increasing the number of strong interferers for each cell leads to the rise of the backhaul traffic. Compared with soft IC with quantization of the reliability information algorithm reported in [5], the proposed DID-RMP algorithm significantly reduces the backhaul requirement with the increased number of interference.

V. SIMULATIONS

In the simulations, we assume $\rho_{m,o}$ is zero, $\rho_{m,d} = 1$, and strongly received interference have $\rho_{m,n} = 0.5$. All BSs are assumed to have the same SNR and the interfering BSs are also assumed to have the same SIR. To evaluate the performance of the distributed turbo system, we select a rate $R = 1/2$ convolutional code with polynomial $[7, 5]_{\mathrm{oct}}$. The coded bits are modulated as QPSK symbols before transmission. The decoding is performed by a max-log-MAP decoder, and the block length is set to 1024. The number of detector and decoder iterations is fixed to ten. The loop of network-level IC performed by the network stops with the fourth iteration, and the number of cells in each cluster is $\phi = 1$, if not otherwise stated. For the soft IC scheme [4], [5], a uniform quantizer is applied to quantize the soft estimates. Without significant information loss compared with the unlimited backhaul (UB) performance, six quantization bits per real dimension backhaul traffic is assumed [12].

In Fig. 3, the proposed DID-RMP outperforms the soft IC scheme [4], [5], and the improvement increases with a higher number of strong interferers ζ. With $\zeta = 3$, the proposed scheme achieves about 3 dB of gain, as compared with the system using hard cancelation at the target BER $= 10^{-3}$. There are three dominant interferers at the BS's receiver. Some weaker interference below a certain threshold can be modeled as Gaussian noise and integrated into the noise term. Therefore, we treat weak interference as noise, and the system considers only strong interference and noise.

In Fig. 4, the average number of tentative decision in the network is shown. The number of tentative decisions Γ decreases as more iterations are performed. In the proposed DID-RMP scheme, only indexes are exchanged; the backhaul traffic becomes lower in each iteration due to the fact that Γ is getting smaller. On the other hand, the soft IC scheme [4], [5] does not benefit from the iterations due to the requirement of updating the soft estimates. We can also see from the plots that the average number of candidates quickly converges to 1, which means low additional detection complexity is required for each BS. Compared with Fig. 3, the target BER region ranged from 10^{-3} to 10^{-4}, and the corresponding SNR is ranged from 8 to 10 dB. The average number of tentative decisions per symbol is below 3 for $\zeta = 3$. In the case of two strong interferers, we can see that negligible additional backhaul overhead is required.

All the previous results are bounded by the isolated cell performance since $\phi = 1$, and there is only one pair of receive and transmit antennas available in each cluster; no array gain and diversity can be obtained. However, in Fig. 5, we assume a cooperating four-cell network with $\zeta = 2$ strong interferers per BS; we group the four cells into two clusters, and $\phi = 2$. A 2×2 distributed MIMO system is created in each cluster, and the interference is mitigated between two clusters.

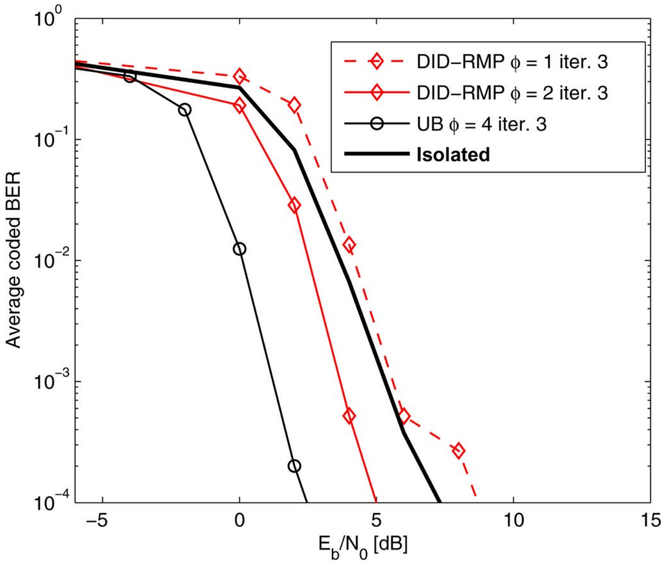

Fig. 5. Performance of a cooperating four-cell network with $\zeta = 2$ strong interferers per BS. We group the four cells into two clusters $\phi = 2$ and single cluster $\phi = 4$.

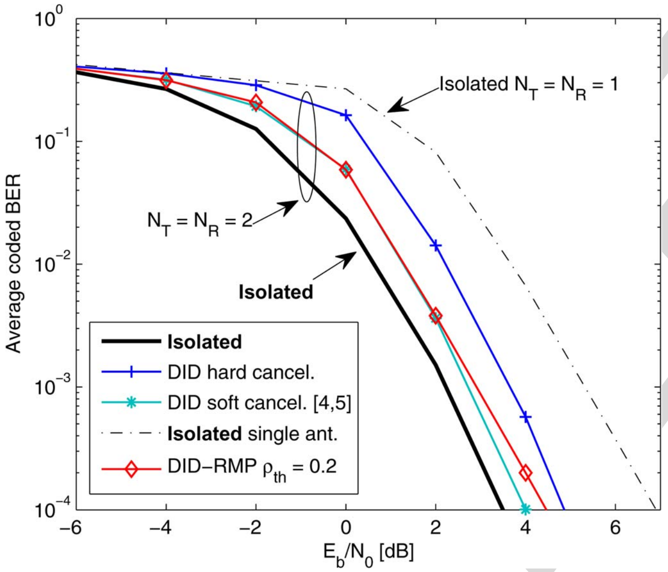

Fig. 6. Performance of a cooperating two-cell network with $\zeta = \{1, 1\}$ strong interferers per BS in which we assume a single cell for each cluster $\phi = 1$ and $N_R = N_T = 2$ antennas for each BS and user. A user-based cancelation is used. The DID soft cancelation is performed according to [4] and [5].

We also investigate a single cluster system with $\phi = 4$, assuming UB, a 4 × 4 distributed MIMO system is created, and high diversity and array gain are obtained.

Fig. 6 shows a system model with multiple-antenna users and BSs; we build a two-cell network model where each cell has a single user that has $N_T = 2$ transmit antennas. The BSs for the cells also have $N_R = 2$ antennas ready for detection. Each BS receives the desired signal as well as the interference from the adjacent cells. Due to the fact that two data streams are seen as an interfering signal, we use $\zeta = \{1, 1\}$ to discriminate from the single-antenna case. In this simulation, a user-based cancelation is used, the IC is only achieved between the users instead of data streams, and the cochannel interference from a single user remains. By using a fixed threshold $\rho_{\mathrm{th}} = 0.2$ for a cooperative two-cell network with multiple data streams for each user, the DID-RMP algorithm can provide a near soft-IC performance.

VI. CONCLUSION

We have discussed multiuser multicell detection through BSC in an uplink high-frequency reuse scenario. DID has been introduced as an interference mitigation technique for networked MIMO systems. We have compared soft and hard information exchange and cancelation schemes and proposed a novel hard information exchange strategy based on the concept of RMP. The proposed DID-RMP algorithm significantly reduces the backhaul data compared with the soft information exchange while it obtains a better BER performance.

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Distributed Iterative Detection With Reduced Message Passing for Networked MIMO Cellular Systems

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Abstract—**This paper considers base station cooperation (BSC) strategies for the uplink of a multiuser multicell high-frequency reuse scenario where distributed iterative detection (DID) schemes with soft/hard interference cancelation (IC) algorithms are studied. The conventional distributed detection scheme exchanges soft-symbol estimates with all cooperating BSs. Since a large amount of information needs to be shared via the backhaul, the exchange of hard bit information is preferred; however, performance degradation is experienced. In this paper, we consider a reduced message passing (RMP) technique in which each BS generates a detection list with the probabilities for the desired symbol that are sorted according to the calculated probability. The network then selects the best detection candidates from the lists and conveys the index of the constellation symbols (instead of double-precision values) among the cooperating cells. The proposed DID-RMP achieves intercell interference (ICI) suppression with low backhaul traffic overhead compared with the conventional soft bit exchange and outperforms the previously reported hard/soft information exchange algorithms.**

Index Terms—**Base station cooperation (BSC), distributed iterative detection (DID), iterative (turbo) processing, multiple-input–multiple-output (MIMO), multiuser detection.**

I. INTRODUCTION

The growing demand for mobile multimedia applications requires higher data rates and reliable links between base stations (BSs) and mobile users. The improvement of system capacity can be achieved by introducing higher frequency reuse and microcell planning [1], [2]. In such a network configuration, higher spectral efficiency is obtained; however, the intercell interference (ICI) becomes dominant at the cell edges, particularly in an aggressive frequency reuse scenario [1], [3]. The application of interference mitigation techniques is necessary in these systems to prevent a reduced data rate of the users located at the cell edge and improve system fairness [14], [15].

Strategies to deal with the ICI in the system uplink include joint multiuser detection (JMD) [3], [8], [9], [16] and distributed iterative detection (DID) [5], [7], [12], [18], [19]. In terms of JMD, the BSs for each cell make the received signals available to all cooperating cells. With this setting, the receivers not only use the desired signal energy but also the energy from the interferers leading to a much improved received signal-to-interference-plus-noise ratio (SINR). Both array and diversity gains are obtained, resulting in a substantial increase in system capacity [12]. Despite the optimality of JMD, it needs to exchange all the quantized received signals between the cooperative BSs via a wired or microwave backbone network, which brings about huge background data traffic [2], [5]. To reduce the backhaul traffic, clusters may be applied, a group of BSs can form a cluster, and the JMD can be performed in a central unit. The information is exchanged within the cluster, which reduces the backhaul and the complexity. However, the JMD-based structure has many restrictions: 1) the performance degrades at the boundaries of the clusters; 2) the central units are required to support a large number of users in the cluster that introduces high detection complexity; and 3) it requires transmission of quantized received signals over the wired network to the central unit that causes high backhaul traffic [1], [5].

To circumvent the aforementioned problems, an advanced interference mitigation technique for distributed receivers is introduced. A DID structure is presented as an alternative to JMD for cooperative detection with affordable backhaul traffic between cooperating BSs [4], [5], [12]. With the DID scheme, iterative processing is performed at the network level. The receiver detects each user stream in its corresponding cell and iteratively refines the estimate of the transmitted symbol with the help of the information provided by other cooperating cells. Each BS detects the desired user/stream only, the other interfering signal is canceled or treated as noise [10], [13]. The output of the receiver is used to reconstruct the transmitted symbol, and this estimate is conveyed to the cooperating BSs. Each BS exchanges its estimates with the neighbors, the reconstructed interferers are canceled from the received signal, and the power of the interference reduces as more iterations are performed. With DID, the detection complexity is restricted to the number of data streams inside the cell [5]. Despite their advantages, DID techniques have the drawback that the interference cancelation (IC) is performed at the network level, the exchange of soft information brings about high backhaul traffic, and the iterative detection delay must be minimized.

In the remaining part of this paper, we focus on interference mitigation techniques [7], [14], [15] dealing with the multiuser multicell detection through BS cooperation (BSC) in an uplink interference-limited aggressive frequency reuse scenario. In the proposed DID with reduced message passing (DID-RMP) algorithm, the cooperating BSs exchange information while performing interference mitigation based on single-user or multiuser detection. Instead of exchanging the soft estimates introduced in [5], [10], and [12], the proposed algorithm generates a sorted list containing the probability of the constellation symbols given the channel information. The indexes of the constellation symbols with high probability are exchanged via the backhaul link. A selection unit (SU) is also proposed in the network to provide the best candidates from the list. The indexes are exchanged among the BSs in an iterative manner, and the system improves the estimate of the desired signal with each iteration loop. The indexed interference at the cooperating BSs is subtracted from the received signal, resulting in a reduced interference level and more reliable data estimates. The simulation results indicate that the proposed DID-RMP scheme is able to outperform the soft-symbol cancelation technique reported in [5] and [12] while requiring much less backhaul traffic.

This paper is structured as follows. The system and data model is presented in Section II. In Section III, the iterative detection with RMP is discussed, which also involves soft/hard interference subtraction and the proposed index-based subtraction. The simulation results and the conclusions are presented in Sections IV and V, respectively.

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II. DATA MODEL OF A NETWORKED MULTIPLE-INPUT–MULTIPLE-OUTPUT CELLULAR SYSTEM

We consider an asymmetric multiuser scenario of a networked MIMO cellular system. We assume that the cellular network can detect groups of users that are received by several cooperating BSs [4], [5], [7]. We consider that a number of ϕ cells are grouped into one cluster, that the diversity and array gains can be obtained inside the cluster, and that the interference among the clusters is mitigated through the application of DID schemes. Since we are interested in mitigating the intercluster interference, to simplify our description, we consider the special case $\phi = 1$, where each cell represents a cluster. The scenarios with more cells in the cluster $\phi > 1$ are straightforward.

Let us consider an idealized synchronous uplink single-carrier narrow-band cellular network that aims to capture most of the features of a realistic wireless system with respect to the interference and the need for backhaul. We define M as the number of cooperating BSs and K as the number of users in the cooperating cells, and assume the users and BSs have a single transmit antenna. Extensions to multiple antennas are straightforward and are considered later on. In networked MIMO systems, a limited number of cells can work together in order for the backhaul overhead to be affordable [11]; by increasing the number of cooperating cells, a higher number of interfering links are expected to be dealt with. The increased backhaul traffic is a direct consequence of the BSs dealing with a higher number of interferers. Therefore, the number of cooperating cells should be limited. In this system, the transmitted data of each user are protected by the channel codes separately. A message vector $\boldsymbol{m}_k$ from user k is encoded by a channel code before a bit interleaving operation. The resulting bit sequence $\boldsymbol{b}_k$ has Q entries, and $k = 1, 2, \ldots, K$ are the indexes of the interfering users. The sequence is then divided into groups of J bits each, which are mapped to a complex symbol vector as the output of the user k; this operation is denoted $\boldsymbol{s}_k = [s_{k,1}, \ldots, s_{k,Q_s}] = \mathrm{map}(\boldsymbol{b}_k)$, where $Q_s = Q/J$, and each entry of $\boldsymbol{s}_k$ is taken from a complex constellation $\mathcal{A}$ with power $E\{|s_{k,j}|^2\} = \sigma_s^2$.

A. Data Model for Single-Antenna Users and BSs

A $K \times 1$ symbol vector $\boldsymbol{s}[i] = [s_1[i], s_2[i], \ldots, s_K[i]]^T$ is transmitted simultaneously by all K users. At BS m, the received symbols $r_m[i]$ are given by

$$r_m[i] = \boldsymbol{g}_m[i]\boldsymbol{s}[i] + v_m[i], \qquad 1 \le i \le Q_s \tag{1}$$

where $\boldsymbol{g}_m[i] \in \mathbb{C}^{1\times K}$, $m = 1, \ldots, M$; the entry $[i]$ is the time index; and $v_m[i]$ denotes the additive zero-mean complex Gaussian noise with variance $E\{v[i]v[i]^*\} = \sigma_v^2$.

The entries of the $1 \times K$ row vector $\boldsymbol{g}_m$ are the element-wise product of $h_{m,k}$ and $\sqrt{\rho_{m,k}}$, where $h_{m,k}$ is the complex channel realization from the kth user to the mth BS with independent and identically distributed (i.i.d.) $\mathcal{CN}(0,1)$. The coefficients $\rho_{m,k}$ reflect the path loss with respect to BS m and user k. Similarly to [5], we separate $r_m[i]$ into four terms expressed by

$$\begin{aligned} r_m[i] &= g_{m,d}s_d[i] + \sum_{n\in\mathcal{C}_m} g_{m,n}s_n[i] + \sum_{n\in\hat{\mathcal{C}}_m} g_{m,o}s_o[i] + v[i], \\ &= \sqrt{\rho_{m,d}}h_{m,d}s_d[i] + \sqrt{\rho_{m,n}} \sum_{n\in\mathcal{C}_m} h_{m,n}s_n[i] \\ &\quad + \sqrt{\rho_{m,o}} \sum_{n\in\hat{\mathcal{C}}_m} h_{m,o}s_o[i] + v[i] \end{aligned} \tag{2}$$

where the first term denotes the desired signal (indexed by $_d$), and the second and third terms denote the strong interference and the weak interference (indexed by $_n$ and $_o$, respectively). Coefficients ρ_n and ρ_o characterize the channel gains with strong and weak interferers, respectively. The set of indexes of all strongly received interference at BS m is denoted $\mathcal{C}_m$ and the weakly received interference is denoted $\hat{\mathcal{C}}_m$.

It is shown in [4] and [5] that the strongest interferers dominate the total ICI. In this model, we constrain the number of strongly received signals to $m_n \le 5$. For example, in a system with $K = M = 4$, the number of strong interferers $\zeta = 2$, the weak interference $\rho_{m,o}$ is equal to zero, and the desired user is denoted $\rho_{m,d} = 1$; then, the coupling matrix is formed as

$$\boldsymbol{P} = \begin{bmatrix} 1 & \rho_{m,n} & \rho_{m,n} & 0 \\ 0 & 1 & \rho_{m,n} & \rho_{m,n} \\ \rho_{m,n} & 0 & 1 & \rho_{m,n} \\ \rho_{m,n} & \rho_{m,n} & 0 & 1 \end{bmatrix}. \tag{3}$$

The coupling matrix $\boldsymbol{P}$ is introduced to describe the configuration of an interference model of a multiuser multicell system. Its diagonal values indicate the power of the link between the BS and the user within the local cell. The off-diagonal values denote the power of interfering links between the BS and the interfering users from other cells. The channel realization of the whole cooperative system $\boldsymbol{G}$ is obtained by the element-wise product of $\boldsymbol{P}$ and $\boldsymbol{H}$ with the elements $h_{m,k}$ following i.i.d. $\mathcal{CN}(0,1)$.

In this configuration, we assume the BSs have the ability to know from which cells the interfering signals are coming. The BS in the desired cell then notifies the BS of the interfering cells and obtains the estimated transmit signal from that cell to perform IC. The exchanged interfering information is transmitted via a wired backhaul that connects all the BSs in the network.

The SNR is defined as the ratio of the desired signal power at the receiver side and the noise power, which is mathematically described as $\mathrm{SNR}_d := 10\log_{10}(E\{\|h_{m,d}s_d\|^2\})/E\{\sigma_v^2\}$. Let us also denote the average signal-to-interference ratio (SIR) of the desired user k as follows:

$$\mathrm{SIR}_d := 10\log_{10} \times \frac{E\{\|g_{m,d}s_d\|^2\}}{\sum_{n\in\mathcal{C}_m} E\{\|g_{m,n}s_n\|^2\} + \sum_{n\in\hat{\mathcal{C}}_l} E\{\|g_{m,o}s_o\|^2\}}. \tag{4}$$

B. Data Model for Multiple-Antenna Users and BSs

Here, a data model for networked MIMO systems in which the users and BSs are equipped with multiple antennas is discussed. The scalar $r_m[i]$ and vector $\boldsymbol{g}_m[i]$ in (1) are now described in the vector $\boldsymbol{r}_m[i]$ and matrix $\boldsymbol{G}_m[i]$ forms, respectively, as given by

$$\boldsymbol{r}_m[i] = \boldsymbol{G}_m\boldsymbol{z}[i] + \boldsymbol{v}_m[i] \tag{5}$$

where $\boldsymbol{r}_m \in \mathbb{C}^{N_R\times 1}$ is the received vector for the mth BS, and $\boldsymbol{G}_m \in \mathbb{C}^{N_R\times KN_T}$ is the combined channel matrix with $\boldsymbol{G}_m = [\boldsymbol{G}_{m,1}, \ldots, \boldsymbol{G}_{m,k}, \ldots, \boldsymbol{G}_{m,K}]$, where $\boldsymbol{G}_{m,k} \in \mathbb{C}^{N_R\times N_T}$ denotes the channel between user k and BS m. Note that each user has N_T transmit antennas, and each BS has N_R receive antennas. The quantity $\boldsymbol{z} \in \mathbb{C}^{KN_T\times 1}$ is the collection of the data streams from the K users $\boldsymbol{z} = [\boldsymbol{s}_1^T, \ldots, \boldsymbol{s}_K^T]^T$ and $\boldsymbol{s}_k \in \mathbb{C}^{N_T\times 1}$. Equation (2) can be rewritten as

$$\begin{aligned} \boldsymbol{r}_m[i] &= \boldsymbol{G}_{m,d}\boldsymbol{s}_d[i] + \sum_{n\in\mathcal{C}_m} \boldsymbol{G}_{m,n}\boldsymbol{s}_n[i] + \sum_{n\in\hat{\mathcal{C}}_m} \boldsymbol{G}_{m,o}s_o[i] + \boldsymbol{v}_m[i], \\ &= \sqrt{\rho_{m,d}}\boldsymbol{H}_{m,d}\boldsymbol{s}_d[i] + \sqrt{\rho_{m,n}} \sum_{n\in\mathcal{C}_m} \boldsymbol{H}_{m,n}\boldsymbol{s}_n[i] \\ &\quad + \sqrt{\rho_{m,o}} \sum_{n\in\hat{\mathcal{C}}_m} \boldsymbol{H}_{m,o}\boldsymbol{s}_o[i] + \boldsymbol{v}_m[i] \end{aligned} \tag{6}$$

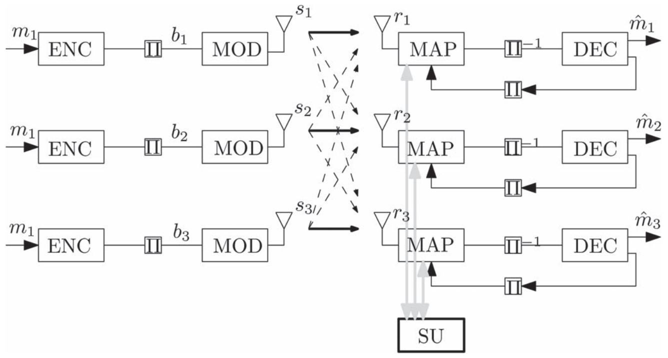

Fig. 1. Example configuration showing a cooperating three-cell network. The dashed lines between the transmitter and the receiver denote the ICI, whereas the solid lines denote the desired signal.

where we assume that the N_T antennas for each user have the same channel gain coefficients ρ_n and ρ_o. The coupling matrix given in (3) and the definition of SNR and SIR can be generalized accordingly.

To simplify the description of the proposed structure and its traditional counterparts, we first employ the single-antenna case $N_T = N_R = 1$ in the following.

III. DISTRIBUTED ITERATIVE DETECTION WITH REDUCED MESSAGE PASSING

Here, the decision-aided DID structure is described in detail. Earlier, the distributed iterative signal processing in an interference-limited cellular network is reviewed. In the following, the soft and hard parallel IC algorithms are based on the quantized estimates from the cooperating BSs. The end of this section is devoted to the description of the proposed DID-RMP.

A. *Decision-Aided Distributed Iterative Detection*

The setup for performing the distributed detection with the information exchange between BSs is shown in Fig. 1. The K users' data are separately coded and modulated to complex symbols after bit interleaving. At each BS, the received signal $r_m[i]$ is the collection of the transmitted signal and the Gaussian noise.

In addition, each BS equips a communication interface for exchanging information with the cooperating BSs. The information is in the form of a bit sequence that represents the quantized soft estimates. The interface is capable of transmitting and receiving information. Via these interfaces, each cooperating BS is connected to a device, namely the SU, and is ready to receive and transmit the information for cooperation. The proposed SU has very limited computational power and it can be integrated with BSs in the network.

In each BS, a block of received signals $r_m[i]$ is used by the maximum *a posteriori* (MAP) demapper to compute the *a posteriori* probability in the form of log-likelihood ratios (LLRs), which are given by

$$\Lambda_1^p\left[b_{j,k}[i]\right] = \log \frac{P\left[b_{j,k}[i] = +1 | r_m[i]\right]}{P\left[b_{j,k}[i] = -1 | r_m[i]\right]} \tag{7}$$

where the equation can be solved by using Bayes' theorem, and we leave the details to [10] and [13]. The detector and the decoder are serially concatenated to form a "turbo" structure, the *extrinsic* information is exchanged by the two soft-input–soft-output components. We denote the *intrinsic* information provided by the decoder as $\Lambda_2^p[b_{j,k}[i]]$, and the bit probability is $P[b_{j,k}[i]] = \log(P[b_{j,k}[i] = +1])/(P[b_{j,k}[i] = -1])$. From [10], the bitwise probability is obtained by

$$\begin{aligned} P\left[b_{j,k}[i] = \bar{b}_j\right] &= \frac{\exp\left(\bar{b}_j \Lambda_2^p\left[b_{j,k}[i]\right]\right)}{1 + \exp\left(\bar{b}_j \Lambda_2^p\left[b_{j,k}[i]\right]\right)} \\ &= \frac{1}{2}\left[1 + \bar{b}_j \tanh\left(\frac{1}{2}\Lambda_2^p\left[b_{j,k}[i]\right)\right)\right] \end{aligned} \tag{8}$$

where $\bar{b}_j = \{+1, -1\}$. Let us simplify the notation $P[s_k[i]] := P[s_k[i] = c_q]$, where c_q is an element chosen from the constellation $\mathcal{A} = \{c_1, \ldots, c_q, \ldots, c_A\}$. The symbol probability $P[s_k[i]]$ is obtained from the corresponding bitwise probability, and assuming the bits are statistically independent, we have

$$\begin{aligned} P\left[s_k[i]\right] &= \prod_{j=1}^{J} P\left[b_{j,k}[i] = \bar{b}_j\right] \\ &= \frac{1}{2^J}\prod_{j=1}^{J}\left[1 + \bar{b}_j \tanh\left(\frac{1}{2}\Lambda_2^p\left[b_{j,k}[i]\right]\right)\right]. \end{aligned} \tag{9}$$

From (8) and (9), we can easily conclude that $\sum_{|\mathcal{A}|} P[s_k[i]] = 1$. The symbol likelihood $P[s_k[i]]$ can be used to evaluate the reliability of the recovered symbol. A higher probability of detection of $s_k[i]$ can be associated with a higher reliability of estimation of that symbol.

B. *Soft Interference Cancelation*

The soft IC has first been reported in an iterative multiuser code-division multiple-access (CDMA) systems in [10] and later extended by several works [4], [13], [19]. In the algorithm [4], the soft replicas of ICI are constructed and subtracted from the received signal vector as

$$\tilde{r}_{m,k}[i] = r_m[i] - \boldsymbol{g}_m \tilde{\boldsymbol{u}}_k[i] \tag{10}$$

and the replica of the transmitted symbol vector $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{K \times 1}$ is obtained as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{s}_1[i], \ldots, \tilde{s}_{k-1}[i], 0, \tilde{s}_{k+1}[i], \ldots, \tilde{s}_K[i]\right]^T \tag{11}$$

where the estimates of $s_k[i]$ are calculated as

$$\tilde{s}_k[i] = E\left\{s_k[i]\right\} = \sum_{c_q \in \mathcal{A}} c_q P\left[s_k[i] = c_q\right]. \tag{12}$$

The first-order and second-order statistics of the symbols are obtained from the symbol *a priori* probabilities as $\sigma_{\text{eff}}^2 = \text{var}\{s_k[i]\} = E\{|s_k[i]|^2\} - |\tilde{s}_k[i]|^2$ and $E\{|s_k[i]|^2\} = \sum_{c_q \in \mathcal{A}} |c_q|^2 P[s_k[i] = c_q]$.

In the case that the users and BSs are equipped with multiple antennas, then (10) can be reformulated as

$$\tilde{\boldsymbol{r}}_{m,k}[i] = \boldsymbol{r}_m[i] - \boldsymbol{G}_m \tilde{\boldsymbol{u}}_k[i]. \tag{13}$$

The soft IC procedure can be considered in two cases. In the first case, the cancelation is performed in terms of users rather than data streams, and we name this case as user-based cancelation. In this case, the interfering signals received from other cell users are canceled, but the interference between the antenna data streams of the desired user remains. Mathematically, the replica of the transmitted symbol vector $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{KN_T \times 1}$ is defined as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{\boldsymbol{s}}_1^T[i], \ldots, \tilde{\boldsymbol{s}}_{k-1}^T[i], 0, \tilde{\boldsymbol{s}}_{k+1}^T[i], \ldots, \tilde{\boldsymbol{s}}_K^T[i]\right]^T \tag{14}$$

where $0 \in \mathbb{Z}^{N_T \times 1}$ and $\tilde{\boldsymbol{s}}^T_{\kappa \neq k}[i], \kappa = 1, \ldots, K \in \mathbb{C}^{N_T \times 1}$. The remaining signal after the IC is the combination of all the data streams transmitted from user k and the noise.

In the second case, we consider each independent antenna data stream received by the BSs, and disregarding which users send them; we name this case as data-stream-based cancelation. In this case, the BSs consider interference in terms of streams instead of users. In a mathematical point of view, the replica of the transmitted signal for stream-based IC $\tilde{\boldsymbol{u}}_k[i] \in \mathbb{C}^{KN_T \times 1}$ is defined as

$$\tilde{\boldsymbol{u}}_k[i] = \left[\tilde{\boldsymbol{s}}_1^T[i], \ldots, \tilde{\boldsymbol{s}}_{k-1}^T[i], \tilde{\boldsymbol{s}}_k'^{T}[i], \tilde{\boldsymbol{s}}_{k+1}^T[i], \ldots, \tilde{\boldsymbol{s}}_K^T[i]\right] \qquad (15)$$

where the entry $\tilde{\boldsymbol{s}}'_k$ is obtained as $\tilde{\boldsymbol{s}}_k'^{T}[i] = [\tilde{s}_1[i], \ldots, \tilde{s}_{n_t-1}[i], 0, \tilde{s}_{n_t+1}[i], \ldots, \tilde{s}_{N_T}[i]]^T$. By using this scheme, all the interfering streams are removed after the cancelation procedure.

This soft-interference-cancelation-based algorithm generally outperforms hard IC since it considers the reliability of the cancelation procedure. However, the performance heavily depends on the quantization level. Exchanging the quantized soft bits or LLRs convey reliability information among BSs and involves a large amount of backhaul data per cell per iteration, which make soft IC unattractive.

C. Hard Interference Cancelation

With the hard IC, the estimates of the interfering symbols are the constellation symbols. In this case, the quantization is performed for each estimated symbol. Equation (11) is rewritten as

$$\begin{aligned}\hat{\boldsymbol{u}}_k[i] = [&Q(\tilde{s}_1[i]), \ldots, Q(\tilde{s}_{k-1}[i]), 0,\\ &Q(\tilde{s}_{k+1}[i]), \ldots, Q(\tilde{s}_K[i])]^T \qquad (16)\end{aligned}$$

where $Q(\cdot)$ is the slicing function that depends on the constellation adopted. The constellation indexes are exchanged among the cooperating BSs. Since no reliability information is included, the cooperation procedure requires significantly less backhaul traffic as compared with the soft interference procedure. All the detected information symbols are exchanged in the initial iteration, and in the subsequent iterations, only the symbols with the constituent bits that have flipped between the iterations are exchanged. The indexed constellation symbols are reconstructed at the neighboring BSs and subtracted from the received signal, the residual noise is considered equal to zero, and $\sigma^2_{\text{eff}} = \sigma^2_v$. In the hard IC configuration, the backhaul traffic can be further brought down by introducing a reliability check of the symbols and by exchanging reliable symbols. It is worth mentioning that, by introducing the reliability check, the error propagation effect can be effectively mitigated. The selected unreliable estimates can be either refined or excluded from the IC procedure. The performance improvement over the hard IC scheme is investigated in [6].

D. Distributed Iterative Detection With Reduced Message Passing

The hard IC is performed in a way that the effect of all the detected symbols, but the intended one, are removed from the received signal. It ignores the reliability of the estimated symbols used for IC, but ignoring the reliability may lead to error propagation, which can significantly deteriorate the performance. The soft IC is then introduced to combat error propagation by using quantized soft symbols; however, this procedure requires more iterations to obtain a good performance that increases the detection delay. In addition, the sharing of quantized symbol estimates requires a higher bandwidth across the network, and the bitwise quantization for every symbol brings about higher complexity. In the following, we present a method that is able to address these problems and keep a low backhaul requirement.

By organizing the probabilities obtained by (9) in decreasing order of values, a list of tentative decisions of $s_k[i]$ is obtained in each BS, as given by

$$\mathcal{L}_k[i] \triangleq \{c_1, c_2, \ldots, c_\tau\}_k \qquad (17)$$

where the number of candidates is $1 \leq \tau \leq |\mathcal{A}|$. Probabilities $\Pr[c_1] \geq \Pr[c_2] \geq \cdots \Pr[c_\tau]$, where $\Pr[c_q] \triangleq P[s_k[i] = c_q | r_m]$ is the probability of the transmitted signal is c_q given r_m. For the simplicity of computation, we only keep candidates with probability higher than a threshold such as $P[s_k[i]] \geq \rho_{\text{th}}$ from the list. Threshold ρ_{th} may be fixed or varied in terms of SINR. It is also worth mentioning that failing to optimize the threshold ρ_{th} would result in either heavy backhaul traffic (ρ_{th} too low) or unacceptable performance (ρ_{th} too high). The optimization of ρ_{th} can be performed by maximizing the SINR of the data streams with the constraint of the maximum allowable backhaul traffic.

For symbols transmitted by each user, we generate a tentative decision list $\mathcal{L}_k$. By listing all the combinations of the elements across K users, a length Γ tentative decision list is formed at the corresponding SU. Each column vector on the list denotes a possible symbol vector $\boldsymbol{s}'_l$, where $l = 1, \ldots, \Gamma$. The size of the list is obtained by

$$\Gamma = \prod_{k=1}^{K} |\mathcal{L}_k|, \quad 1 \leq \Gamma \ll |\mathcal{A}|^K \qquad (18)$$

where $|\cdot|$ denotes cardinality. To obtain an improved performance, the maximum-likelihood (ML) rule can be used to select the best among the Γ candidate symbol vectors. Note that, without a designated threshold, an ML search over the whole vector space $\Gamma = |\mathcal{A}|^K$ is performed, which is equivalent to joint ML detection and provides a full diversity order with prohibitive backhaul requirements and detection complexity. However, the DID-RMP algorithm obtains a higher diversity order than that of "perfect IC" with a much smaller candidate list (compared with ML) due to the threshold ρ_{th} and its effective selection of candidates.

The threshold value should be adequately set to generate an affordable list size Γ. The ML criterion, which is equivalent to the minimum Euclidean distance criterion, computes the ML solution as given by

$$\boldsymbol{s}'_{\text{ML}} = \arg \min_{l=1,\ldots,\Gamma} \|\boldsymbol{r}[i] - \boldsymbol{G}\boldsymbol{s}'_l[i]\|^2 \qquad (19)$$

where $\boldsymbol{r}[i] = [r_1[i], \ldots, r_m[i], \ldots, r_M[i]]^T$, and $\boldsymbol{G} = [\boldsymbol{g}_1^T, \ldots, \boldsymbol{g}_m^T, \ldots, \boldsymbol{g}_M^T]^T$ are received signals and the user channels for all cooperating cells.

In the given expression, the knowledge of $\boldsymbol{g}_m$ and the received signal $r_m[i]$ for each cell is required to be passed to the SU, which may lead to high backhaul traffic. Additionally, as a central point, there is high computational power demand for the SU to choose the best candidate from the list. To circumvent the aforementioned problems, we introduce the method of RMP that is able to distribute the normalization operations to each cooperating BSs.

Distributed Selection Algorithm: The Euclidean distance $\boldsymbol{d} = \boldsymbol{r}[i] - \boldsymbol{G}\boldsymbol{s}'_l[i]$ in (19) is obtained by

$$\|\boldsymbol{d}\| \triangleq \sqrt{|d_{1,m}|^2 + \cdots + |d_{k,m}|^2} \qquad (20)$$

where $d_{k,m} = r_m[i] - \boldsymbol{g}_m \boldsymbol{s}'_l[i]$, $\boldsymbol{g}_m[i] \in \mathbb{C}^{1 \times K}$, $m = 1, \ldots, M$, and $\boldsymbol{s}'_l[i] \in \mathbb{C}^{K \times 1}$. For each BS, we separately calculate the minimum partial weights by

$$l_m^{\min} = \arg \min_{l} |r_m[i] - \boldsymbol{g}_m \boldsymbol{s}'_l[i]|^2. \qquad (21)$$

The channel information $\boldsymbol{g}_m$ is known to the local BS m, the candidate with the minimum Euclidean distance index $l_m^{\min}$ is obtained by the SU

TABLE I
ALGORITHM 1: DID-RMP ALGORITHM

Algorithm 1 DID-RMP Algorithm

```
Initialization $r_m$, $\boldsymbol{g}_m$, $\Lambda_2^p[b_{j,k}[i]] \leftarrow \mathbf{0}$, $TI$.
for $k \leftarrow 1, \ldots, K$ {user k} do
    $m \leftarrow k$
    for $j \leftarrow 1, \ldots, J$ {bit-mapping} do
        $P[b_{j,k}[i] = \bar{b}_j] \leftarrow \frac{1}{2}\left[1 + \bar{b}_j \tanh\left(\frac{1}{2}\Lambda_2^p[b_{j,k}[i]]\right)\right]$
    end for
    $P\left[s_k[i]\right] \leftarrow \prod_{j=1}^{J} P[b_{j,k}[i] = \bar{b}_j]$
    $\mathcal{L}_k[i] \triangleq \{c_1, c_2, \ldots, c_\tau\}_k$ {candidate list}
    SU $\Leftarrow 1, \ldots, \tau$ {index sharing}
    $\boldsymbol{s}'_l[i] \Leftarrow$ SU {index fetching}
    $l_m^{\min} \leftarrow \arg\min_l |r_m[i] - \boldsymbol{g}_m \boldsymbol{s}'_l[i]|^2$
    $\tilde{r}_k[i] = r_k[i] - \boldsymbol{h}_k \tilde{\boldsymbol{u}}_k^{\mathrm{ML}}[i]$ {interference cancellation}
    for $lo \leftarrow TI$ {turbo iterations} do
        $\Lambda_1^p[b_{j,k}[i]] \leftarrow$ interleaving aprior, MAP detection
        $\Lambda_2^p[b_{j,k}[i]] \leftarrow$ deinterleaving aprior, max-log-MAP decoding
    end for
end for
Decision of systematic bit is obtained via sign$\{\Lambda_2^p[b_{j,k}[i]]\}$
```

via backhaul, and an enhanced detection is obtained. In each iteration, the received signal is subtracted by

$$\tilde{r}_k[i] = r_k[i] - \boldsymbol{h}_k \tilde{\boldsymbol{u}}_k^{\mathrm{ML}}[i] \tag{22}$$

where the selected candidate $\tilde{\boldsymbol{u}}_k^{\mathrm{ML}}$ consists of

$$\tilde{\boldsymbol{u}}^{\mathrm{ML}} = \left[\tilde{s}_1^{\mathrm{ML}}, \ldots, \tilde{s}_{k-1}^{\mathrm{ML}}, 0, \tilde{s}_{k+1}^{\mathrm{ML}}, \ldots, \tilde{s}_K^{\mathrm{ML}}\right]. \tag{23}$$

With this multiple candidate structure, an enhanced ICI suppression is obtained. The indexes of the symbols on the tentative decision list $\mathcal{A}_k$ are propagated among the neighboring BSs that require reduced backhaul traffic compared with that of the soft signal cancelation algorithm. Additionally, as more cancelation iterations are performed, the size of the list reduces as the recovered bits are more reliable. This further decreases the backhaul traffic with the following iterations, which is not the case with the approach that adopts a soft IC strategy. We can translate the proposed DID-RMP algorithm as follows. In a cooperative network serving several users, if one estimate is not reliable enough to perform IC, the system uses the side information (symbol indexes) provided by other cooperative cells to refine this estimate; therefore, a more reliable IC in the network level is obtained. The algorithm of the proposed DID-RMP method is summarized in Table I.

For an IC-based method, the performance is bounded by the bit error rate (BER) of isolated cells, the single BS in each cell can only provide a diversity order of one. On the other hand, in an extreme case, if the algorithm searches the whole vector space $\Gamma = |\mathcal{A}|^K$, a full diversity order is obtained, and the optimal detection requires exponentially increased complexity. The DID-RMP algorithm however provides a tradeoff between complexity/backhaul and performance by varying the threshold ρ_{th}, and a higher diversity order is obtained with a short candidate list due to its effective selection of candidates.

IV. COMPLEXITY AND BACKHAUL ANALYSIS

A. *Complexity*

In terms of the complexity, a network-wide parallel IC is adopted to remove the cochannel interference by removing the estimates of the interfering symbols based on the *a priori* LLRs obtained from the single-input–single-output channel decoder. For each IC iteration, the reconstruction operations (8) and (9) require $\mathcal{O}(2J)$ real-valued multiplications. These symbol estimates are used to cancel interference in the receiver vector/scalar (22), which require $\mathcal{O}(K-1)$ complex multiplications. The remaining term is then detected by a soft output MAP detector; the computation of per-stream *a posteriori* LLRs requires $\mathcal{O}(J)$ real-valued multiplication and $\mathcal{O}(3JK)$ complex multiplications, where J is the modulation level that denotes the number constituent bits per symbol, and K is the total number of users for detection.

Unlike a centralized methods that requires $\mathcal{O}(J^K)$ complex multiplications or $\mathcal{O}(K^2(MK))$ operations for the filter-based signal processing [14]–[16], in the proposed DID-RMP structure, each BS separately calculates the minimum partial weights in each cell (21) at the cost of only $\mathcal{O}(\Gamma K)$ complex multiplications and send the constellation indexes to the SU. Therefore, the SU is used as memory storage of constellation indexes with no computational requirement. The proposed SU is incorporated to minimize the computational requirement for the SU and maximize the overall performance across the cells.

To reduce the detection complexity of the proposed DID-RMP algorithm, list sphere decoders [13] and their variants can be used to generate this candidate list with much lower complexity as compared with the optimal ML detector. Furthermore, the MMSE/zero-forcing (MMSE/ZF)-based nonlinear detectors can be used to perform iterative detection as well. The detector first separates the spatially multiplexed data streams and converts the MMSE estimates into bit-level LLRs; then, the procedure of (17)–(19) can be applied. However, for MMSE/ZF-based methods, by fixing an allowable backhaul traffic, a worse BER performance is expected due to its suboptimal performance. To address this, the authors suggest an upgraded version of the successive IC algorithm called multiple-feedback successive interference cancelation [6] to detect the symbols. This algorithm considers the reliability of estimated symbols and refine those unreliable ones. Since this algorithm has a near ML performance with low complexity, we expect a similar performance with the ML-based decoder introduced here.

B. *Backhaul Requirement*

The backhaul requirement for a conventional cooperating cellular system with soft information exchange depends on the resolution of quantization for channel state information, the resolution of quantization for the signal received from each antennas, the number of cooperating BSs, and the number of strong interferers at the receiver side. Whenever a hard information exchange is adopted, the backhaul requirement is significantly reduced with the sacrifice of the detection performance. By calculating the minimum partial weights and exchanging the indexes of candidate symbols, DID-RMP introduces a tradeoff between backhaul requirement and performance.

Fig. 2 shows the backhaul traffic as a function of the number of strong interferers ζ. As QPSK modulation is used, two bits are required to index the constellation symbols to perform hard IC. In practical joint and distributed cooperative networks, the data compression techniques are useful for transmitting the soft-quantized symbols. For fairness, we compare both three and six bits per dimension for quantizing the soft symbol; the data compression is only considered in this section but not in the BER simulations in the following. With the DID-RMP algorithm, the list size Γ does not grow exponentially with the increase in the modulation level (e.g., from QPSK to 16-QAM), but a higher backhaul requirement is expected due to an increasing number of unreliable estimates. On the other hand, if the backhaul reaches its

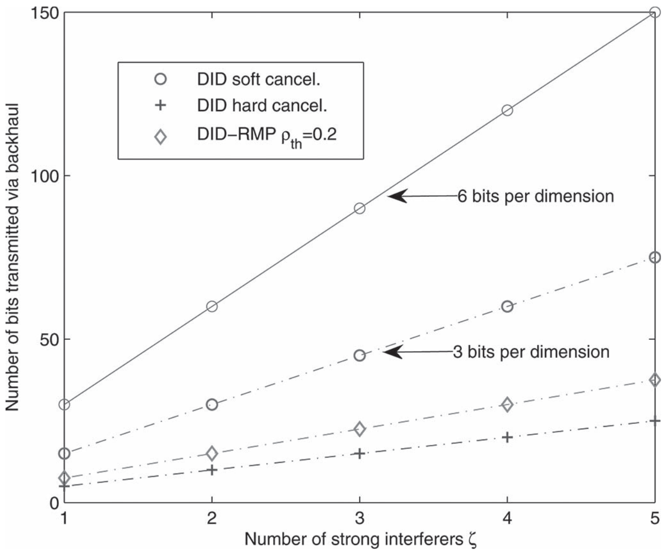

Fig. 2. Number of bits exchanged per symbol detection in a nine-cell network. The number of bits required via backhaul increases with the number of strong interfering links within the cooperative network.

maximum allowable traffic, performance degradation is also expected. The plots indicate that increasing the number of strong interferers for each cell leads to the rise of the backhaul traffic. Compared with soft IC with quantization of the reliability information algorithm reported in [5], the proposed DID-RMP algorithm significantly reduces the backhaul requirement with the increased number of interference.

V. SIMULATIONS

In the simulations, we assume $\rho_{m,o}$ is zero, $\rho_{m,d} = 1$, and strongly received interference have $\rho_{m,n} = 0.5$. All BSs are assumed to have the same SNR and the interfering BSs are also assumed to have the same SIR. To evaluate the performance of the distributed turbo system, we select a rate $R = 1/2$ convolutional code with polynomial $[7,5]_{\mathrm{oct}}$. The coded bits are modulated as QPSK symbols before transmission. The decoding is performed by a max-log-MAP decoder, and the block length is set to 1024. The number of detector and decoder iterations is fixed to ten. The loop of network-level IC performed by the network stops with the fourth iteration, and the number of cells in each cluster is $\phi = 1$, if not otherwise stated. For the soft IC scheme [4], [5], a uniform quantizer is applied to quantize the soft estimates. Without significant information loss compared with the unlimited backhaul (UB) performance, six quantization bits per real dimension backhaul traffic is assumed [12].

In Fig. 3, the proposed DID-RMP outperforms the soft IC scheme [4], [5], and the improvement increases with a higher number of strong interferers ζ. With $\zeta = 3$, the proposed scheme achieves about 3 dB of gain, as compared with the system using hard cancelation at the target BER $= 10^{-3}$. There are three dominant interferers at the BS's receiver. Some weaker interference below a certain threshold can be modeled as Gaussian noise and integrated into the noise term. Therefore, we treat weak interference as noise, and the system considers only strong interference and noise.

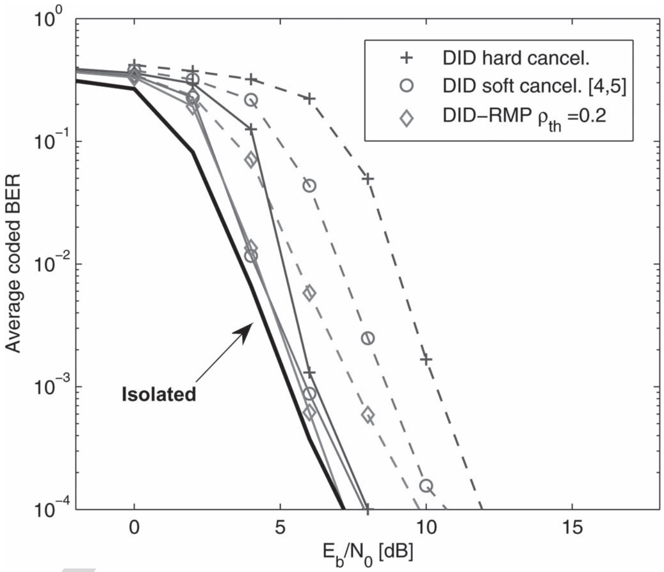

Fig. 3. SNR versus average BER. The solid lines denote a cooperating four-cell network with $\zeta = 2$ strong interferers per cell. The dashed lines denote a cooperating network with nine cells with $\zeta = 3$ strong interferers per cell. The DID soft cancelation is performed according to [4] and [5].

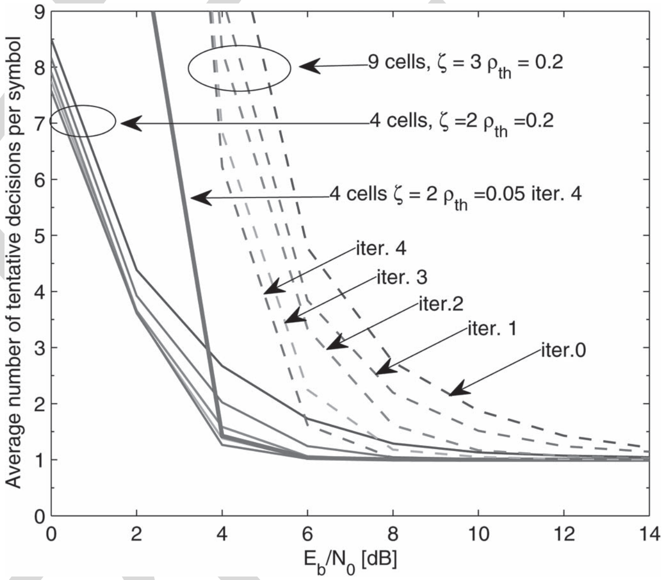

Fig. 4. Number of tentative decisions Γ decreases as the SNR increases. With a smaller threshold ρ_{th} selected, more decision candidates are generated, particularly in the low SNR region.

In Fig. 4, the average number of tentative decision in the network is shown. The number of tentative decisions Γ decreases as more iterations are performed. In the proposed DID-RMP scheme, only indexes are exchanged; the backhaul traffic becomes lower in each iteration due to the fact that Γ is getting smaller. On the other hand, the soft IC scheme [4], [5] does not benefit from the iterations due to the requirement of updating the soft estimates. We can also see from the plots that the average number of candidates quickly converges to 1, which means low additional detection complexity is required for each BS. Compared with Fig. 3, the target BER region ranged from 10^{-3} to 10^{-4}, and the corresponding SNR is ranged from 8 to 10 dB. The average number of tentative decisions per symbol is below 3 for $\zeta = 3$. In the case of two strong interferers, we can see that negligible additional backhaul overhead is required.

All the previous results are bounded by the isolated cell performance since $\phi = 1$, and there is only one pair of receive and transmit antennas available in each cluster; no array gain and diversity can be obtained. However, in Fig. 5, we assume a cooperating four-cell network with $\zeta = 2$ strong interferers per BS; we group the four cells into two clusters, and $\phi = 2$. A 2×2 distributed MIMO system is created in each cluster, and the interference is mitigated between two clusters.

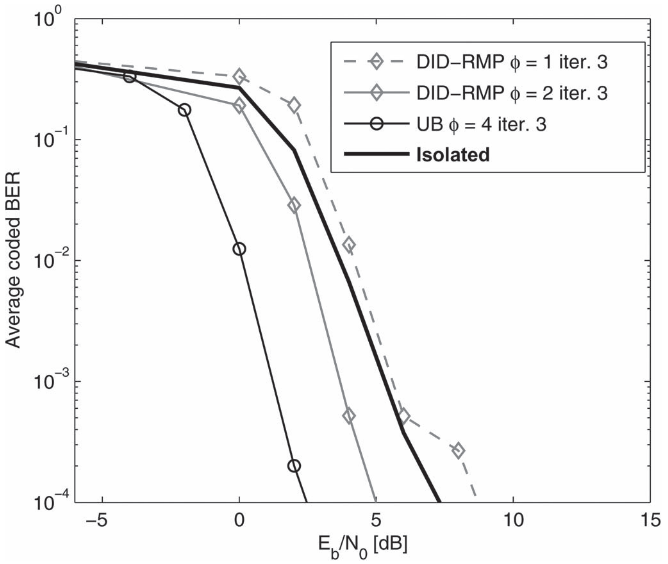

Fig. 5. Performance of a cooperating four-cell network with $\zeta = 2$ strong interferers per BS. We group the four cells into two clusters $\phi = 2$ and single cluster $\phi = 4$.

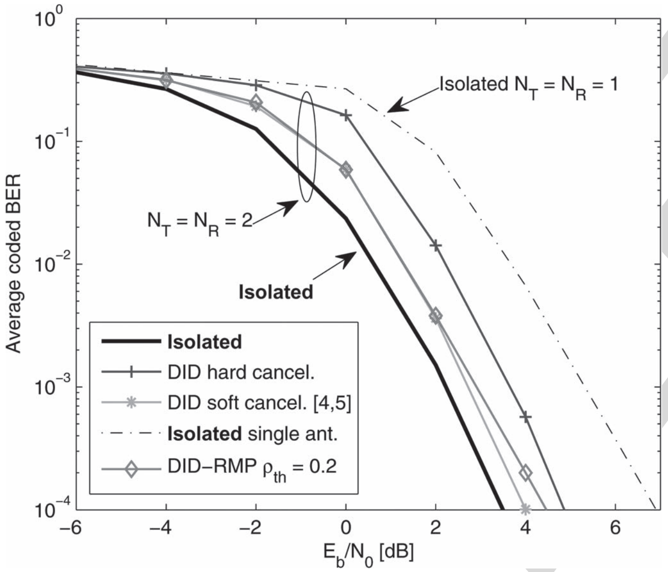

Fig. 6. Performance of a cooperating two-cell network with $\zeta = \{1, 1\}$ strong interferers per BS in which we assume a single cell for each cluster $\phi = 1$ and $N_R = N_T = 2$ antennas for each BS and user. A user-based cancelation is used. The DID soft cancelation is performed according to [4] and [5].

We also investigate a single cluster system with $\phi = 4$, assuming UB, a 4 × 4 distributed MIMO system is created, and high diversity and array gain are obtained.

Fig. 6 shows a system model with multiple-antenna users and BSs; we build a two-cell network model where each cell has a single user that has $N_T = 2$ transmit antennas. The BSs for the cells also have $N_R = 2$ antennas ready for detection. Each BS receives the desired signal as well as the interference from the adjacent cells. Due to the fact that two data streams are seen as an interfering signal, we use $\zeta = \{1, 1\}$ to discriminate from the single-antenna case. In this simulation, a user-based cancelation is used, the IC is only achieved between the users instead of data streams, and the cochannel interference from a single user remains. By using a fixed threshold $\rho_{\mathrm{th}} = 0.2$ for a cooperative two-cell network with multiple data streams for each user, the DID-RMP algorithm can provide a near soft-IC performance.

VI. CONCLUSION

We have discussed multiuser multicell detection through BSC in an uplink high-frequency reuse scenario. DID has been introduced as an interference mitigation technique for networked MIMO systems. We have compared soft and hard information exchange and cancelation schemes and proposed a novel hard information exchange strategy based on the concept of RMP. The proposed DID-RMP algorithm significantly reduces the backhaul data compared with the soft information exchange while it obtains a better BER performance.

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