Robust leakage-based distributed precoder for cooperative multicell systems

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Published in *The Journal of Engineering*; Received on 2nd June 2014; Accepted on 16th June 2014

Abstract: Coordinated multipoint (CoMP) from long term evolution (LTE)-advanced is a promising technique to enhance the system spectral efficiency. Among the CoMP techniques, joint transmission has high communication requirements, because of the data sharing phase through the backhaul network, and coordinated scheduling and beamforming reduces the backhaul requirements, since no data sharing is necessary. Most of the available CoMP techniques consider perfect channel knowledge at the transmitters. Nevertheless for practical systems this is unrealistic. Therefore in this study the authors address this limitation by proposing a robust precoder for a multicell-based systems, where each base station (BS) has only access to an imperfect local channel estimate. They consider both the case with and without data sharing. The proposed precoder is designed in a distributed manner at each BS by maximising the signal-to-leakage-and-noise ratio of all jointly processed users. By considering the channel estimation error in the design of the precoder, they are able to reduce considerably the impact of these errors in the system's performance. The results show that the proposed scheme has improved performance especially for the high signal-to-noise ratio regime, where the impact of the channel estimation error may be more pronounced.

1 Introduction

Multicell cooperation is a promising solution for cellular wireless systems to mitigate intercell interference, improving system fairness and increasing capacity in the years to come [1–3], and thus is already under study in LTE-advanced under the coordinated multipoint concept [4]. There are several cooperative multicell approaches depending on the amount of information shared by the transmitters through the backhaul network and where the processing takes place, that is, centralised if the processing takes place at the central unit (CU) [5] or distributed [2, 6] if it takes place at different transmitters. Coordinated centralised approaches promise larger spectral efficiency gains than distributed interference coordination techniques, but typically at the price of larger backhaul and more severe synchronisation requirements [3].

Some sub-optimal centralised precoding schemes have been discussed in [5]. The interference is eliminated by joint and coherent coordination of the transmission from the base stations (BSs) in the network, assuming that they share all downlink signals. In [7], inner bounds on capacity regions for downlink transmission were derived with or without BS cooperation and under per-antenna power or sum-power constraint. Two centralised multicell precoding schemes based on the waterfilling technique have been proposed in [8]. It was shown that these techniques achieve close to optimal weighted sum rate performance. Based on the statistical knowledge of the channels, the CU performs a centralised power allocation and jointly minimises the outage probability of the user terminals (UTs) [9]. In [10], a clustered BS coordination is enabled through a multicell block diagonalisation (BD) strategy to mitigate the effects of interference in multicell multiple-input–multiple-output (MIMO) systems. A BD cooperative multicell scheme was proposed in [11] where the weighted UTs sum-rate achievable is maximised. Non-linear centralised multicell precoding was considered in [12].

Distributed precoding approaches, where the precoder vectors are computed at each BS in a distributed fashion, have been proposed in [13] for the particular case of two UTs and generalised for K UTs in [14]. It is assumed that each BS has only the knowledge of local channel state information (CSI) and based on that a parameterisation of the beamforming vectors used to achieve the outer boundary of the achievable rate region was derived. Distributed precoding schemes based on zero-forcing (ZF) criterion with several centralised power allocation approaches, which minimise the average bit error-ratio (BER) and sum of inverse of signal-to-noise ratio was proposed in [15]. In [13–15], it was considered that the BSs share the entire data of the all jointly processed users, whereas in [16] the distributed precoding was designed so that the transmitters do not share the data which fall into the interference channel framework. One of the considered criteria to design the precoders was the signal-to-leakage-and-noise (SLNR) ratio maximisation, introduced first in the context of multiuser MIMO [17]. This technique balances the received signal power of the target user against the interference power imposed on the remaining users. Basically, it combines the benefits of both the egoistic distributed maximum ratio transmission and the altruistic ZF techniques [18]. In the previous distributed approaches, the precoders were designed by assuming perfect knowledge of local CSI. In [13–18], the authors assume that perfect channel knowledge is available. Nevertheless, this is not a realistic assumption for practical scenarios. In this paper, we tackle this limitation. More specifically, the main contributions of this paper are the following:

- Design of a new SLNR-based precoder, where the channel errors are explicitly taken into account.
- In the precoder design, we tackle both the case where the BSs share their users data (extension of the paper presented in [13–15]) and where there is no data sharing (extension of the paper presented in [16]).
- By using the SLNR metric, we are able to design each user's precoder independently of the others, which enable the derivation of a closed-form solution for the proposed robust precoder, unlike the signal-to-interference-and-noise metric.

The remainder of this paper is organised as follows: Section 2 presents the multicell system model for both scenarios with and without data sharing. In Section 3, we derive the proposed robust distributed precoder for these two multicell-based approaches. Section 4 presents the main performance results. The conclusions will be drawn in Section 5.

Notations: Throughout this paper, we will use the following notations. Lowercase letters, boldface lowercase letters and boldface uppercase letters are used for scalars, vectors and matrices, respectively. $(.)^{\mathrm{H}}$ represents the conjugate transpose operator, $\mathbb{E}[.]$ represents the expectation operator, $\boldsymbol{I}_N$ is the identity matrix of

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size $N \times N$, $\mathcal{CN}(.,\ .)$ denotes a circular symmetric complex Gaussian vector and $\|\boldsymbol{h}\|$ denotes the norm of vector $\boldsymbol{h}$.

2 System model

We consider two downlink multicell multiple-input–single-output (MISO)-based systems: in the first approach we consider that the BSs know the data symbols of all joint processing users which are shared by the backhaul network, and in the second one the BSs only know its own data symbols and therefore the backhaul network is not needed. It is assumed, for both approaches, that each BS has only access to an imperfect local channel estimate, that is, the channels between a given BS and all the joint processing users.

2.1 Multicell system with data sharing

We consider B BSs, each equipped with N_{t_b} antennas, transmitting to K single antenna UTs sharing the same physical channel, that is, the information for all UTs is transmitted at the same frequency band. The data symbols of all joint processing users are shared by the backhaul network as shown in Fig. 1. Under the assumption of linear precoding, the signal transmitted by the BS b is given by

$$\boldsymbol{x}_b = \sum_{k=1}^{K} \sqrt{p_{b,k}}\boldsymbol{w}_{b,k}s_k \tag{1}$$

where $p_{b,k}$ represents the power allocated to UT k at the BS b, $\boldsymbol{w}_{b,k} \in \mathrm{C}^{N_{t_b}\times 1}$ is the distributed precoder of user k at BS b with unit norm, that is, $\|\boldsymbol{w}_{b,k}\| = 1, \quad b = 1, \ \ldots, B, \ k = 1, \ \ldots, K$. The data symbol s_k, with $\mathbb{E}\left[|s_k|^2\right] = 1, \forall k$, is intended for UT k and is assumed to be available at all BSs.

The received signal at the UT k can be expressed as

$$y_k = \sum_{b=1}^{B} \boldsymbol{h}_{b,k}^{\mathrm{H}}\boldsymbol{x}_b + n_k \tag{2}$$

where $\boldsymbol{h}_{b,k} \in C^{N_{t_b}\times 1}$ represents the channel between the BS b and user k and $n_k \sim \mathcal{CN}(0,\ \sigma^2)$ is the Gaussian noise.

From (1) and (2) the received signal at UT k can be decomposed in

$$y_k = \underbrace{\sum_{b=1}^{B} \sqrt{p_{b,k}}\boldsymbol{h}_{b,k}^{\mathrm{H}}\boldsymbol{w}_{b,k}s_k}_{\text{desired signal}} + \underbrace{\sum_{b=1}^{B} \boldsymbol{h}_{b,k}^{\mathrm{H}} \sum_{j=1, j\neq k}^{K} \sqrt{p_{b,j}}\boldsymbol{w}_{b,j}s_j}_{\text{multiuser multicell interference}} + \underbrace{n_k}_{\text{noise}} \tag{3}$$

2.2 Multicell system without data sharing

Here we also consider a downlink multicell MISO-based system, where B BSs, each equipped with N_{t_b} antennas, transmit data to K single antenna UTs sharing the same physical channel. For this scenario, each BS only serves one user and has only access to its data symbols. Therefore for this case the backhaul network is not needed, since there is no data sharing between BSs, see Fig. 2. However, the BSs have access to an imperfect version of channels between themselves and all the joint processing users such that coordinated precoding can be performed. In the following, we consider that UT k is server by BS b_k. Under the assumption of linear precoding, the signal transmitted by BS b_k is given by

$$\boldsymbol{x}_{b_k} = \sqrt{P_{b_k}}\boldsymbol{w}_{b_k}s_{b_k} \tag{4}$$

where $\boldsymbol{w}_{b_k} \in \mathrm{C}^{N_{t_b}\times 1}$, with $\|\boldsymbol{w}_{b_k}\|^2 = 1$, is the precoder at BS b_k, s_{b_k} with $\mathbb{E}\left[|s_{b_k}|^2\right] = 1$, denotes the BS b_k data symbol intended for UT k and P_{b_k} is the transmit power of the b_kth BS. The received signal at UT k, *served by BS* b_k is now given by

$$y_k = \underbrace{\sqrt{P_{b_k}}\boldsymbol{h}_{b_k,k}^{\mathrm{H}}\boldsymbol{w}_{b_k}s_{b_k}}_{\text{desired signal}} + \underbrace{\sum_{i=1, i\neq b_k}^{B} \sqrt{P_i}\boldsymbol{h}_{i,k}^{\mathrm{H}}\boldsymbol{w}_i s_i}_{\text{multiuser multicell interference}} + \underbrace{n_k}_{\text{noise}} \tag{5}$$

where $\boldsymbol{h}_{i,k} \in \mathrm{C}^{N_{t_b}\times 1}$ represents the channel between the BS i and user k.

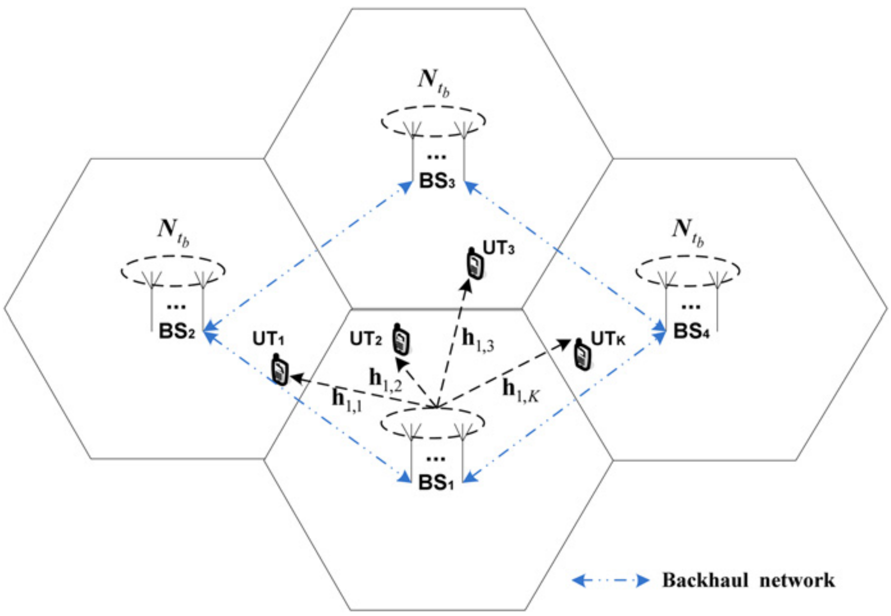

Fig. 1 *Considered data sharing scenario with K UTs (illustrated for B = 4 BSs equipped with* N_{t_b} *antennas)*

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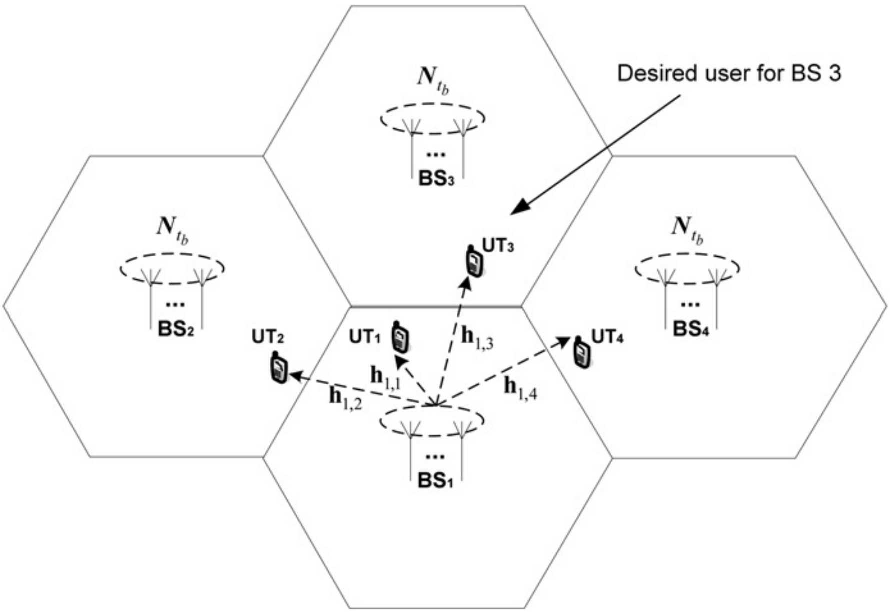

Fig. 2 *Considered scenario without data sharing (illustrated for B = 4 BSs equipped with N_{t_b} antennas each one served a single user)*

2.3 Channel estimation error model

In both scenarios, we assume that BS b has only knowledge of an estimate of its own channels $\boldsymbol{h}^{\mathrm{H}}_{b,j}$, $j = 1, \ldots, K$ and has no access to the channels from the other BSs. The channel estimate at the transmitter b will be modelled as

$$\hat{\boldsymbol{h}}^{\mathrm{H}}_{b,j} = \boldsymbol{h}^{\mathrm{H}}_{b,j} - \boldsymbol{e}^{\mathrm{H}}_{b,j} \tag{6}$$

where $\boldsymbol{e}_{b,j} \in \mathbb{C}^{N_{t_b} \times 1}$ represents the overall channel estimation error and its elements are assumed to be independent identically distributed zero-mean complex Gaussian distributed with variance σ_h^2 and spatially white. The variance of the channel estimation error σ_h^2 is assumed to be known at all BSs [19].

3 Robust leakage precoder

3.1 Multicell system with data sharing

From (3), we verify that the power of the desired signal component coming from BS b at user k is

$$I_{b,k} = p_{b,k} \left| \boldsymbol{h}^{\mathrm{H}}_{b,k} \boldsymbol{w}_{b,k} \right|^2 \tag{7}$$

Likewise the interference power induced by BS b on UT k is given by

$$L_{b,k} = p_{b,k} \sum_{\substack{j=1 \\ j \neq k}}^{K} \left| \boldsymbol{h}^{\mathrm{H}}_{b,j} \boldsymbol{w}_{b,k} \right|^2 \tag{8}$$

BS b has only an imperfect estimate of its channel vectors. Let us define $\boldsymbol{A}_{b,k} = \hat{\boldsymbol{h}}_{b,k} \hat{\boldsymbol{h}}^{\mathrm{H}}_{b,k} + \sigma_h^2 \boldsymbol{I}$ and $\boldsymbol{D}_{b,k} = \sum_{j \neq k} \hat{\boldsymbol{h}}_{b,j} \hat{\boldsymbol{h}}^{\mathrm{H}}_{b,j} + (K-1)\sigma_h^2$, then by averaging over the channel errors the desired signal component and channel leakage power are as follows

$$\bar{I}_{b,k} = p_{b,k} \boldsymbol{w}^{\mathrm{H}}_{b,k} \left(\hat{\boldsymbol{h}}_{b,k} \hat{\boldsymbol{h}}^{\mathrm{H}}_{b,k} + \sigma_h^2 \boldsymbol{I} \right) \boldsymbol{w}_{b,k} = p_{b,k} \boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{A}_{b,k} \boldsymbol{w}_{b,k} \tag{9}$$

$$\begin{aligned} \bar{L}_{b,k} &= p_{b,k} \boldsymbol{w}^{\mathrm{H}}_{b,k} \left(\sum_{\substack{j=1 \\ j \neq k}}^{K} \hat{\boldsymbol{h}}_{b,j} \hat{\boldsymbol{h}}^{\mathrm{H}}_{b,j} + (K-1)\sigma_h^2 \boldsymbol{I} \right) \boldsymbol{w}_{b,k} \\ &= p_{b,k} \boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{D}_{b,k} \boldsymbol{w}_{b,k} \end{aligned} \tag{10}$$

The equality in (9) and (10) follows from

$$\mathbb{E}\left[\left| \boldsymbol{h}^{\mathrm{H}}_{b,k} \boldsymbol{w}_{b,k} \right|^2 \right] = \boldsymbol{w}^{\mathrm{H}}_{b,k} \left(\hat{\boldsymbol{h}}_{b,k} \hat{\boldsymbol{h}}^{\mathrm{H}}_{b,k} + \sigma_h^2 \right) \boldsymbol{w}_{b,k}, \quad k = 1, \ldots, B$$

In the following, we use the SLNR [17] as a figure of merit for the design of precoders $\boldsymbol{w}_{b,k}$. For this scenario, the SLNR is given by

$$\mathrm{SLNR}(\boldsymbol{w}_{b,k}) = \frac{\bar{I}_{b,k}}{\sigma^2 + \bar{L}_{b,k}} = \frac{\boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{A}_{b,k} \boldsymbol{w}_{b,k}}{\boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{\Delta}_{b,k} \boldsymbol{w}_{b,k}} \tag{11}$$

where $\boldsymbol{\Delta}_{b,k} = \left(\sigma^2 / p_{b,k} \right) \boldsymbol{I} + \boldsymbol{D}_{b,k}$. The aim of BS b is to maximise $\mathrm{SLNR}(\boldsymbol{w}_{b,k})$. The BS b optimisation problem can now be mathematically described by

$$\boldsymbol{w}_{b,k} = \arg \max_{\left\| \boldsymbol{w}_{b,k} \right\|^2 = p_{b,k}} \frac{\boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{A}_{b,k} \boldsymbol{w}_{b,k}}{\boldsymbol{w}^{\mathrm{H}}_{b,k} \boldsymbol{\Delta}_{b,k} \boldsymbol{w}_{b,k}} \tag{12}$$

The merit function of optimisation problem (12) is a Rayleigh quotient [20] and thus the optimum precoder for BS b is given by

$$\begin{aligned} \boldsymbol{w}_{b,k} &= \frac{\bar{\boldsymbol{w}}_{b,k}}{\left\| \bar{\boldsymbol{w}}_{b,k} \right\|}, \quad \bar{\boldsymbol{w}}_{b,k} = \frac{\boldsymbol{C}^{-1}_{b,k} \boldsymbol{v}_{b,k}}{\hat{\boldsymbol{h}}^{\mathrm{H}}_{b,k} \boldsymbol{C}^{-1}_{b,k} \boldsymbol{v}_{b,k}} \\ \boldsymbol{v}_{b,k} &= \max\ \mathrm{eigenvector}\left(\left(\boldsymbol{C}^{-1}_{b,k} \right)^{\mathrm{H}} \boldsymbol{A}_{b,k} \boldsymbol{C}^{-1}_{b,k} \right) \end{aligned} \tag{13}$$

where $\boldsymbol{C}_{b,k}$ denotes the Cholesky decomposition of matrix $\Delta_{b,k}$. The solution given by (13) ensures that $\hat{\boldsymbol{h}}^{\mathrm{H}}_{bk} \boldsymbol{w}_{b,k}$ is real valued and positive. This facilitates the decoding process at the UTs, as a scalar multiplication will not affect the value of the merit function given by (11).

3.2 Multicell system without data sharing: For this case, we obtain for the desired and leakage powers, at BS b_k

$$I_{b_k} = \left| \boldsymbol{h}^{\mathrm{H}}_{b_k,k} \boldsymbol{w}_{b_k} \right|^2 \tag{14}$$

$$L_{b_k} = \sum_{j=1, j \neq k}^{K} \left| \boldsymbol{h}^{\mathrm{H}}_{b_k,j} \boldsymbol{w}_{b_k} \right|^2 \tag{15}$$

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J Eng, 2014, Vol. 2014, Iss. 7, pp. 368–372
doi: 10.1049/joe.2014.0141

Averaging over the channel estimation errors, the corresponding SLNR at BS b_k is

$$\mathrm{SLNR}(\boldsymbol{w}_{b_k}) = \frac{I_{b_k}}{\sigma^2 + L_{b_k}} = \frac{\boldsymbol{w}_{b_k}^{\mathrm{H}} \boldsymbol{A}_{b_k} \boldsymbol{w}_{b_k}}{\boldsymbol{w}_{b_k}^{\mathrm{H}} \boldsymbol{\Delta}_{b_k} \boldsymbol{w}_{b_k}} \tag{16}$$

where $\boldsymbol{A}_{b_k} = \hat{\boldsymbol{h}}_{b_k,k} \hat{\boldsymbol{h}}_{b_k,k}^{\mathrm{H}} + \sigma_h^2 \boldsymbol{I}$, $\boldsymbol{\Delta}_{b_k} = \left(\sigma^2/P_{b_k}\right)\boldsymbol{I} + \boldsymbol{D}_{b_k}$ and $\boldsymbol{D}_{b_k} = \sum_{j=1, j\neq k}^{K} \hat{\boldsymbol{h}}_{b_k,j} \hat{\boldsymbol{h}}_{b_k,j}^{\mathrm{H}} + (B-1)\sigma_h^2$. The aim of BS b_k is to maximise $\mathrm{SLNR}(\boldsymbol{w}_{b_k})$ like in (12). The solution of this optimisation problem is

$$\begin{aligned} \boldsymbol{w}_{b_k} &= \frac{\bar{\boldsymbol{w}}_{b_k}}{\left\| \bar{\boldsymbol{w}}_{b_k} \right\|}, \quad \bar{\boldsymbol{w}}_b = \frac{\boldsymbol{C}_{b_k}^{-1} \boldsymbol{v}_{b_k}}{\hat{\boldsymbol{h}}_{b_k jk}^{H} \boldsymbol{C}_{b_k}^{-1} \boldsymbol{v}_{b_k}} \\ \boldsymbol{v}_{b_k} &= \max \ \mathrm{eigenvector}\left(\left(\boldsymbol{C}_{b_k}^{-1} \right)^{\mathrm{H}} \boldsymbol{A}_{b_k} \boldsymbol{C}_{b_k}^{-1} \right) \end{aligned} \tag{17}$$

where $\boldsymbol{C}_{b_k}$ denotes the Cholesky decomposition of matrix $\boldsymbol{\Delta}_{b_k}$. The solution given by (17) ensures that $\hat{\boldsymbol{h}}_{b_k,k}^{\mathrm{H}} \boldsymbol{w}_{b_k}$ is real valued and positive.

4 Performance results

In this section, we assess the performance of the proposed robust leakage-based precoder both for the scenario with and without data sharing. We compare the proposed method against the non-robust approach. We consider a scenario with $B = 4$, $K = 4$ and $N_{t_b} = 4$. In addition, we consider the same power constraint for all BSs, that is, that $P_b = P_k$, $\forall k \neq b$ for the non-data sharing scenario, and $p_{b,k} = P_b/K$ for the data sharing one. The components of the channels $\boldsymbol{h}_{b,j}$ are assumed to be complex Gaussian, that is, the envelope Rayleigh distributed. The results are presented in terms of average BER as a function of the signal-to-noise ratio $(\mathrm{SNR}) = P_b/\sigma^2$.

In Figs. 3 and 4, we show the impact of the channel estimation on the BER performance, by considering different values for the variance of the estimation error, for the scenario with and without data sharing, respectively. As the robust method takes into account both the contributions of the additive noise and channel estimation error, it achieves improved performance. For example, for the case where $\sigma_h^2 = -5$ dB, and considering the data sharing scenario, the BER of the non-robust approach is lower bounded by 3×10^{-2} and degrades for higher SNR values. For the robust method this bound is reduced to 10^{-3}, a reduction of about 66%. For the scenario without data sharing and for $\sigma_h^2 = -20$ and $\sigma_h^2 = -30$ dB, the improvement is about 40 and 50%, respectively. For this case, the channel estimation error has a higher impact on the BER. This occurs as for the scenario with data sharing each user is served by more than one BS and therefore benefits from a diversity advantage. However, the system complexity is higher as the data symbols of all joint processed users must be shared by the backhaul network. As verified from Figs. 3 and 4, the improvement is higher for lower values of the estimation error.

For the least-squares (LS) channel estimation-based method, the estimation error is expected to be equal to the system SNR, that is, $\sigma_h^2 = \sigma^2$. In Figs. 5 and 6, we show the performance of the proposed method when the LS estimator is used, for the scenario with and without data sharing, respectively. For this case, we verify, that there is a gap of about 1.5 dB (3 dB) from the robust to the non-robust approach and of about 8 dB (8 dB) from the robust to the case where $\sigma_h^2 = 0$, at a target BER of 10^{-3}, for the scenario with (without) data sharing. The gap between the robust and the $\sigma_h^2 = 0$ case is constant over the SNR, contrarily to the case of the non-robust method, which indicates that by using the non-robust method the noise is considerably enhanced.

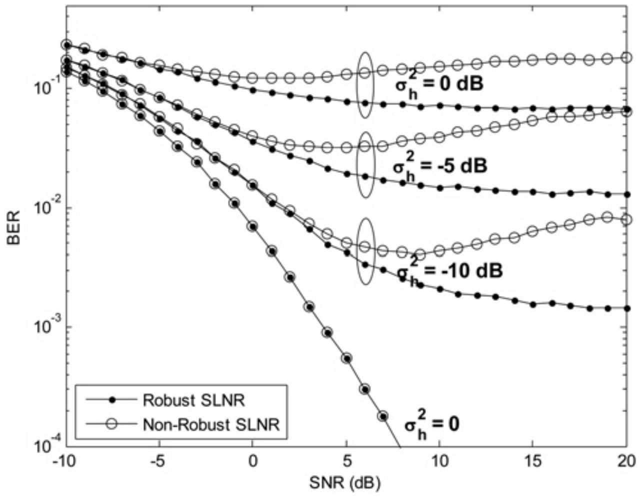

Fig. 3 *Performance evaluation of the robust and non-robust precoding schemes for the multicell system with data sharing and* $\sigma_h^2 = \{-5, -10, -15\}$ *dB,* $B = 4$ *and* $N_{t_b} = 4$

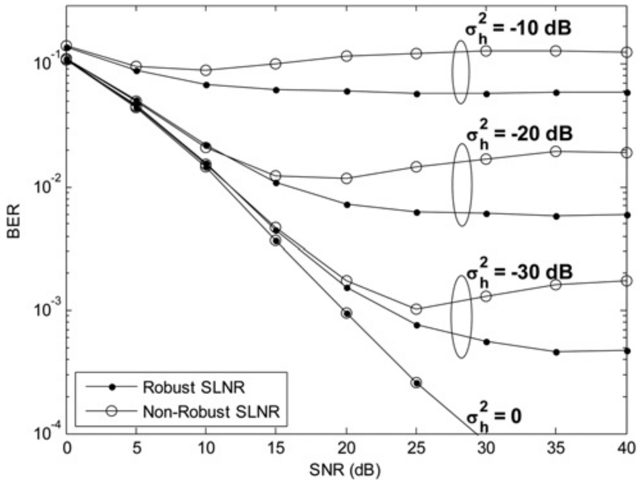

Fig. 4 *Performance evaluation of the robust and non-robust precoding schemes for the multicell system without data sharing and* $\sigma_h^2 = \{-10, -20, -30\}$ *dB,* $B = 4$ *and* $N_{t_b} = 4$

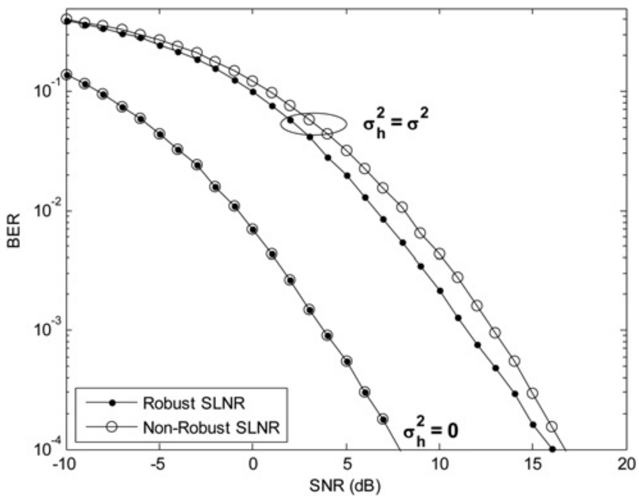

Fig. 5 *Performance evaluation of the robust and non-robust precoding schemes, for the multicell system with data sharing and* $\sigma_h^2 = \{0, \sigma^2\}$*,* $B = 4$ *and* $N_{t_b} = 4$

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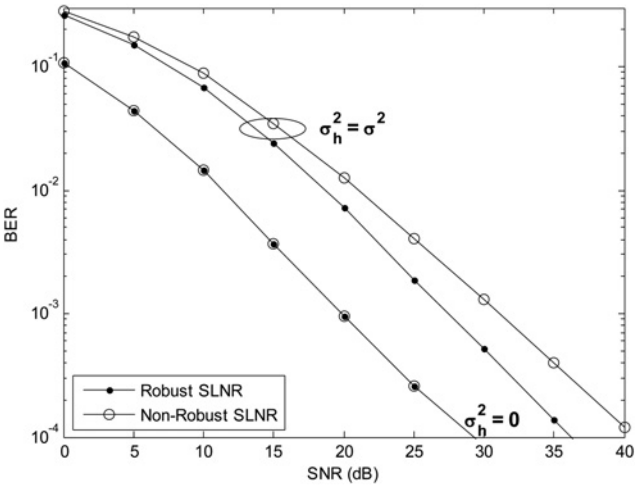

Fig. 6 *Performance evaluation of the robust and non-robust precoding schemes, for the multicell system without data sharing and* $\sigma_h^2 = \{0,\ \sigma^2\}$, *B* = 4 *and* $N_{t_b} = 4$

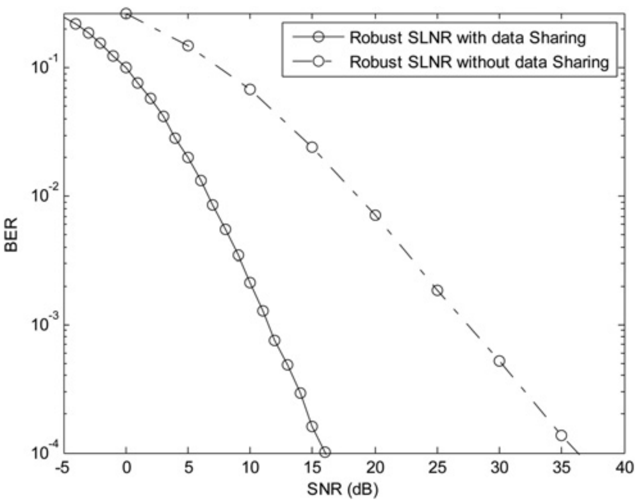

Fig. 7 *Performance evaluation of the robust precoding schemes, with and without data sharing*

Finally, in Fig. 7 we compare the performance of the proposed robust method with and without that sharing, that is, for both scenarios considered. In the data sharing scenario, all BSs transmit data to all users, contrarily to the case without data sharing, where a user only receives its data from one of the BSs. As a consequence, in the data sharing scenario the received data are made available through multiple independent paths increasing the receive signal diversity. This phenomenon is easy to verify from Fig. 7 where the BER curve for the scenario with data sharing, the solid one, has a high diversity order than for the case without data sharing.

5 Conclusions

In this paper, we have proposed a robust distributed precoding method by taking into account the channel estimation errors. A leakage-based approach was considered leading to a closed-form precoder with low complexity. Two approaches were considered: the BSs know the data symbols of all users, shared by the backhaul network and the BSs only know its own data symbols.

The performance of the proposed precoder is considerably better than the non-robust approach for both multi-cell-based systems. By considering the estimation error in the precoder design, we were able to address the shortcomings of the non-robust method by removing the noise enhancement, inherent to such a precoder. The presented results show that the proposed precoder is of special interest for the next generation networks as it deals effectively with the channel errors, which are always present in practical wireless systems.

6 Acknowledgments

This work was supported by the Portuguese FCT (Fundação para a Ciência e Tecnologia) Projects ADIN (PTDC/EEI-TEL/2990/2012), COPWIN (PTDC/EEI-TEL/1417/2012) and HETCOP (PEst-OE/EEI/LA0008/2013).

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