Chapter 5

Physical-Layer Transmission Cooperative Strategies for Heterogeneous Networks

Syed Saqlain Ali, Daniel Castanheira, Adão Silva and
Atílio Gameiro

Additional information is available at the end of the chapter

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Abstract

The deployment of small cells within the boundaries of a macro-cell is considered to be an effective solution to cope with the current trend of higher data rates and improved system capacity. In the current heterogeneous configuration with the mass deployment of small cells, it is preferred that these two cell types coexist over the same spectrum, because acquiring additional spectrum licenses for small cells is difficult and expensive. However, the coexistence leads to cross-tier/inter-system interference. In this context, this contribution investigates interference alignment (IA) methods in order to mitigate the interference of macro-cell base station towards the small cell user terminals. More specifically, we design a diversity-oriented interference alignment scheme with space-frequency block codes (SFBC). The main motivation for joint interference alignment with SFBC is to allow the coexistence of two systems under minor inter-system information exchange. The small cells just need to know what space-frequency block code is used by the macro-cell system and no inter-system channels need to be exchanged, contrarily to other schemes recently proposed. Numerical results show that the proposed method achieves a performance close to the case where full-cooperation between the tiers is allowed.

Keywords: interference alignment (IA), space-frequency block codes (SFBC), downlink (DL), heterogeneous networks (HetNets), small-cell system, macro-cell system

1. Introduction

Due to new generation of wireless user equipment and the proliferation of bandwidth-intensive applications (such as video, mobile broadband modems, tablets and mobile data applications) and the corresponding network load are increasing in exponential manner, where most of this new data traffic is generated indoors. To improve the coverage and provide boost in network capacity, cellular operators are urged to explore different methods, where massive multiple input multiple output (MIMO) [1] and heterogeneous network [2] concepts are two promising technologies to cope with the increased demand for higher data rates as demanded by 5G [3]. Massive MIMO is a large-scale multiuser MIMO strategy that has the capability of communicating with dozens of users at the same time and frequency band. Moreover, the concept of massive MIMO-aided HetNets recently attracted the attention of research community [4]. In this chapter, we focus on the heterogeneous network scenario, where the small cells (SCs) coexist with macro-cells which allow more users to be served. Apart from the capability to provide higher data rates, SCs offer other advantages, such as they are low-power wireless access points (APs) and have low deployment cost, they operate inside the coverage area of a macro-cell, creating a heterogeneous network [5, 6] and they offer great benefits for both operators and users, who get higher data rates, get better coverage and avail new services [7].

Inspired by the features and potential advantages of the small-cell networks, their development and deployment have gained considerable interest in the wireless industry and research communities. On the other hand, these networks also come up with their own challenges. There are significant technical issues related to self-organization, backhauling and interference management that still need to be addressed for their successful rollout and operation [8]. Furthermore, due to huge deployment of SCs within the boundaries of a macro-cell and the cost involved in acquiring additional frequency licenses for small-cells, it is preferred that the macro- and small cells coexist over the same spectrum. However, the coexistence of two systems will result in a number of challenges, namely related to interference management [9], i.e. the cross-tier/inter-system interference. In a coexistence scenario, being the owner of the spectrum, the macro-cell system has the access priority to the available radio spectrum and in the literature of cognitive radio (CR) [10, 11], the macro-cell terminals are denominated as primary users/system; however, the small-cell terminals can only opportunistically access the free space resources of the macro-cell system without generating any interference to it and are denominated secondary. In this context, heterogeneous networks require more dynamic planning and if the system is not carefully designed then it will cause significant interference that affects the performance of both macro-cell and small-cell systems.

In order to cancel interference in heterogeneous networks, different interference mitigation techniques have been proposed [12, 13]. One of the recent and effective approaches to deal with interference issues in heterogeneous networks is the interference alignment (IA) technique [14]. The concept of IA has emerged as an essential approach to align an arbitrary large number of interferers and achieve the maximum degree of freedom (DoF) in interference channels [15, 16]. The problem of limited inter-system information exchange in heterogeneous-based systems using IA has been addressed in some publications [17, 18]. In Ref. [19], it was shown that only 1 bit of information exchange is required between the macro- and small cells to achieve full diversity order at the macro-cell. This work assumed the knowledge of the cross-tier channel at the small cells. Furthermore, the concept of IA has been jointly used with CR in order to mitigate interference in heterogeneous networks. In Ref. [20], authors proposed a practical joint IA and cognitive communication technique in order to deal with the interference of small-cell user terminals (UTs) towards the macro-base station. In this work, three IA methods with different levels of inter-system information exchange

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were proposed, namely: the coordinated, static and uncoordinated approaches. The first method achieves the best performance with very high feedback requirements while the uncoordinated and static methods require no feedback but at the expense of performance degradation. Therefore, to overcome the limitations of coordinated and uncoordinated-static methods, the authors in Ref. [21] investigated a coordinated one-bit method for the uplink of heterogeneous networks.

One of the key aspects in coordinated-based systems is the amount of feedback that needs to be exchanged between the cooperating identities [22], in order to define the overhead requirements needed by the network to avail the benefits from cooperation. When full-coordination is allowed between the two systems, it achieves the best performance and maximum diversity order. On the other hand, when no information is exchanged, the diversity is reduced to minimum as demonstrated in Refs. [20, 21]. In this context, the design of practical schemes that can provide close to optimal performance with limited information exchange is of paramount importance. Therefore, in Ref. [23] we proposed IA-based schemes for the downlink of heterogeneous systems under limited inter-system information exchange. In Ref. [23], we design a new IA-based scheme for the considered heterogeneous systems. Namely, the coordinated $2n$-bit approach, which is an extension of the 2-bit method proposed in Ref. [24]. Moreover, to demonstrate the further reduction of information exchange between the two systems, we proposed a joint IA and space-frequency block code (SFBC) approach [25]. In this chapter, we present the schemes mentioned in Refs. [23, 25] for a general number of antennas at each terminals and for the case where OFDM modulation is considered. Furthermore, for our SFBC-based schemes, we consider a general formulation of the diversity-oriented joint IA and SFBC method that can be applied for any SFBC. For this new method, the small cells just need to sense what SFBC is used by the macro-cell system and no inter-system channels need to be exchanged, contrarily to the previously proposed approaches.

The rest of the chapter is structured as follows: Section 2 introduces the system and signal models for macro-cell and small-cell systems with and without SFBC. In Section 3, we start by summarizing the related work and then the joint IA and SFBC schemes are derived in detail. In Section 4, we discuss the performance ad information exchange requirements for all the methods. In Section 5, we present the numerical results and performance comparison of the proposed methods with others from the literature. Finally, conclusions are provided in Section 6.

2. System model

Let us consider the downlink of a heterogeneous network, where a set of K small-cells are overlaid within the boundaries of a macro-cell, both sharing the same spectrum as depicted in **Figure 1**. The K small-cell base stations (SBSs) are able to cooperate through a backhaul network (e.g. radio over fibre) to a central unit (CU) that allows joint processing of transmitted signals. In this work, we consider the downlink case, i.e. the base stations (BSs) are sending information to the corresponding user equipment (UE). We consider OFDM-based terminals with N_c available subcarriers, but the proposed methods also work with generalized frequency division multiplexing (GFDM), since similarly to OFDM the transmit signals are a linear

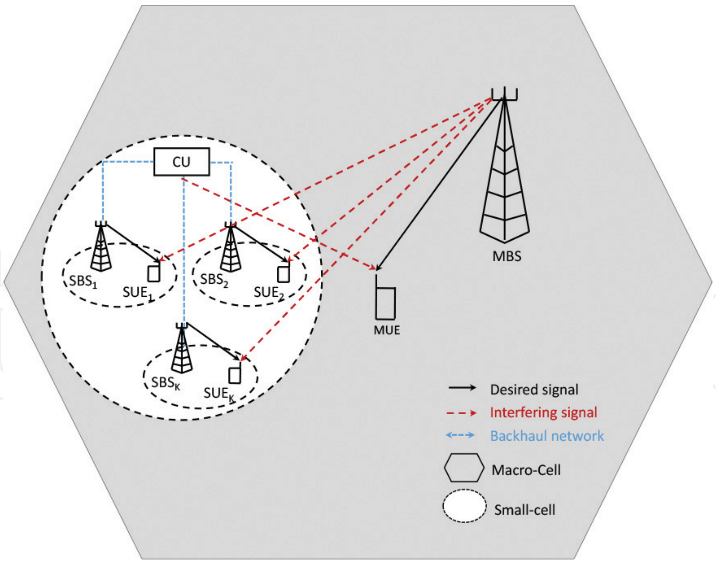

Figure 1. System model: N small cells within the coverage area of macro-cell.

combination of the data symbols [26]. The transmit power per subcarrier for macro-base station (MBS) and SBSs is constraint to P_m and P_s, respectively. We consider that the MBS serves only one user equipment, macro UE (MUE), per subcarrier,[1] and the SBS k serves only the small-cell user equipment k (SUE_k) $k = \{1,\dots K\}$.

2.1. Signal model without SFBC

First, we describe the signal model for the macro- and small-cell systems for the case where no SFBC is employed at the MBS [23]. The block diagram of the considered systems is presented in **Figure 2**. At the macro-cell system, we assume that the MBS and MUE have M_m and N_m antennas, respectively. The transmitted signal ($\mathbf{x}_m^{f_n}$) at the MBS on subcarrier f_n is given by

$$\mathbf{x}_m^{f_n} = \gamma_m(\mathbf{V}_m^{f_n}\mathbf{d}_m^{f_n}), \tag{1}$$

where $\gamma_m^2 = P_m/tr(\mathbf{V}_m^{f_n H}\mathbf{V}_m^{f_n})$, $\mathbf{V}_m^{f_n}\in\mathbb{C}^{M_m N_m}$ and $\mathbf{d}_m^{f_n}\in\mathbb{C}^{N_m}$ denote a normalizing constant, the precoder and the transmitted symbols at the MBS, respectively. The received signal in the frequency domain at the MUE ($\mathbf{y}_m^{f_n}\in\mathbb{C}^{N_m}$) can be mathematically expressed as

$$\mathbf{y}_m^{f_n} = \underbrace{\mathbf{G}_1^{f_n}\mathbf{x}_m^{f_n}}_{\text{Desired signal}} + \underbrace{\mathbf{G}_2^{f_n}\mathbf{x}_s^{f_n}}_{\text{Interference}} + \mathbf{n}_m^{f_n}. \tag{2}$$

where $\mathbf{x}_s^{f_n}\in\mathbb{C}^{M_s K}$, $\mathbf{G}_1^{f_n}\in\mathbb{C}^{N_m M_m}$,$\mathbf{G}_2^{f_n}\in\mathbb{C}^{N_m M_s K}$ and $\mathbf{n}_m^{f_n}\in\mathbb{C}^{N_m}$ denote the overall transmitted signal

[1]Considering an OFDM/A-based system, the total number of macro-cell users can be significantly larger than one, since different set of resources can be allocated to different users.

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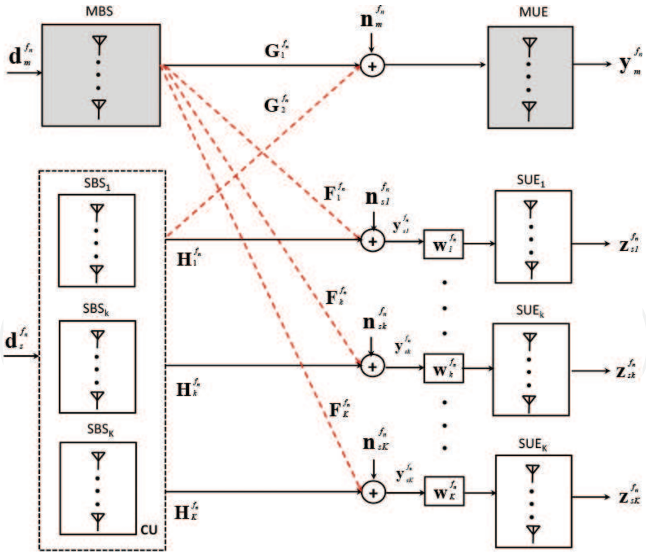

Figure 2. Block diagram of the considered system.

at the small-cell system, the channel between MBS and MUE, the overall channel between CU and MUE (i.e. the channels between the SBSs and the MUE) and the zero-mean white Gaussian noise with variance σ^2, respectively [23]. We assume that at the MBS only $\mathbf{G}_1^{f_n}$ is known and it has no knowledge about the existence of a small-cell system. Furthermore, we assume that the MUE is a high mobility equipment and then $\mathbf{G}_1^{f_n}$ and the precoder $\mathbf{V}_m^{f_n}$ (function of macro-cell channel $\mathbf{G}_1^{f_n}$) change on every transmission time interval (TTI).

In the small-cell system, each SBS has M_s transmit and the SUE_k $k = \{1,\ldots K\}$ has N_s receive antennas. The transmitted signal ($\mathbf{x}_s^{f_n}$) at the CU on subcarrier f_n is expressed as

$$\mathbf{x}_s^{f_n} = \gamma_s(\mathbf{V}_s^{f_n}\mathbf{d}_s^{f_n}), \tag{3}$$

where $\mathbf{V}_s^{f_n} \in \mathbb{C}^{M_s K (N_s - N_m)K}$, $\mathbf{d}_s^{f_n} = [\mathbf{d}_{sk}^{f_n}]_{1 \le k \le K} \in \mathbb{C}^{(N_s - N_m)K}$, $\mathbf{d}_{sk}^{f_n} \in \mathbb{C}^{N_s - N_m}$ and $\gamma_s^2 = P_s / tr(\mathbf{V}_s^{f_n H}\mathbf{V}_s^{f_n})$denote the overall precoder computed at the CU, the concatenation of the K SBSs transmit symbols, the SBS k transmit symbols and a normalizing constant. The received signal after the filter matrix ($W_k^{f_n}$) at the SUE_k is

$$\mathbf{z}_{sk}^{f_n} = W_k^{f_n}(\underbrace{\mathbf{F}_k^{f_n}\mathbf{x}_m^{f_n}}_{\text{Interference}} + \underbrace{\mathbf{H}_k^{f_n}\mathbf{x}_s^{f_n}}_{\text{Desiredsignal}} + \mathbf{n}_{sk}^{f_n}), \tag{4}$$

where $\mathbf{F}_k^{f_n} \in \mathbb{C}^{N_s M_m}$, $\mathbf{H}_k^{f_n} \in \mathbb{C}^{N_s M_s K}$ and $\mathbf{n}_{sk}^{f_n} \in \mathbb{C}^{N_s}$ denote the channel between the MBS and SUE_k, the overall channel between the SBSs and SUE_k and the zero-mean white Gaussian noise with variance σ^2 at SUE_k, respectively. We consider that the SUEs are low mobility terminals[2] and then the channel $\mathbf{F}_k^{f_n}$ can be considered as quasi-static which reduces the overhead required for their estimation [23].

[2]Since the terminals associated with the small cells are mainly indoor/pedestrian users.

2.2. Signal model with SFBC

Now, we consider the signal model with space-frequency coding at the MBS. We consider a block fading MIMO channel, i.e. $\mathbf{G}_1^{f_n} = \mathbf{G}_1 \text{for} f_n = 1, \ldots, F$ and the channel is independent between different blocks of F subcarriers. Thus, the system equation mentioned in Eq. (2), over one block is [27]

$$\mathbf{Y}_m = \mathbf{G}_1\mathbf{X}_m + \mathbf{I}_s + \mathbf{N}_m, \quad (5)$$

where$\mathbf{Y}_m = [\mathbf{y}_m^1, \ldots, \mathbf{y}_m^F]$ is the received signal matrix, $\mathbf{X}_m = [\mathbf{x}_m^1, \ldots, \mathbf{x}_m^F]$ is the transmitted signal, $\mathbf{I}_s = [\mathbf{G}_2^1\mathbf{x}_s^1, \ldots, \mathbf{G}_2^F\mathbf{x}_s^F]$ is the inter-tier interference and $\mathbf{N}_m = [\mathbf{n}_m^1, \ldots, \mathbf{n}_m^F]$ is the zero-mean white Gaussian noise with variance σ^2. The macro-cell system employs an SFBC to encode S_m complex symbols $d_m^1, \ldots, d_m^{S_m}$ chosen from an r-QAM constellation [25]. We consider linear dispersion codes (LD) of the form Ref. [28]

$$\mathbf{X}_m = \sum_{s=1}^{S_m} (\mathbf{A}_m^s \Re\{d_m^s\} + \mathbf{B}_m^s \Im\{d_m^s\}), \quad (6)$$

where $d_m^s = \Re\{d_m^s\} + j\Im\{d_m^s\}$,$m = 1, \ldots, S_m$, $\mathbf{A}_m^s$ and $\mathbf{B}_m^s$ are the codeword matrices. The rate of the LD code is

$$R = \frac{S_m}{F} \log_2(r), \text{bits/subcarrier} \quad (7)$$

Therefore, by rewriting Eq. (5) in column-stacked form we obtain [25]

$$\mathbf{y}_m = (\mathbf{I}_F \otimes \mathbf{G}_1)\mathbf{x}_m + \mathbf{i}_s + \mathbf{n}_m = \mathcal{G}_1 \mathbf{V}_m \mathbf{d}_m + \mathbf{i}_s + \mathbf{n}_m. \quad (8)$$

where $\mathcal{G}_1 = \mathbf{I}_F \otimes \mathbf{G}_1$, $\mathbf{x} = \text{vec}(\mathbf{X})$ is $N_m F$ dimensional, $\mathbf{i}_s = \text{vec}(\mathbf{I}_s)$ is $M_m F$ dimensional, $\mathbf{x}_m = \text{vec}(\mathbf{X}_m) = \mathbf{V}_m \mathbf{d}_m$ is $M_m F$ dimensional, $\mathbf{d}_m = [\Re\{d_m^1\{, \ldots, \Re\{d_m^{S_m}\}, \Im\{d_m^1\}, \ldots, \Im\{d_m^{S_m}\}]^T$, $\mathbf{V}_m = [\text{vec}(\mathbf{A}_1), \ldots, \text{vec}(\mathbf{A}_{S_m}), \text{vec}(\mathbf{B}_1), \ldots, \text{vec}(\mathbf{B}_{S_m})]$ is an $N_m F 2 S_m$ code generator matrix that is an equivalent representation of the LD code.

At the small-cell system, the signal model for the methods with SFBC is similar to one presented previously. Using a similar procedure as in the previous section for the received signal at SUEs, we obtain [27]

$$\mathbf{y}_{sk} = \mathcal{F}_k \mathbf{V}_m \mathbf{d}_m + \mathcal{H}_k \mathbf{x}_s + \mathbf{n}_m, \quad (9)$$

where $\mathbf{y}_{sk} = [(\mathbf{y}_{sk}^1)^T, \ldots, (\mathbf{y}_{sk}^F)^T]^T$, $\mathcal{F}_k = \text{diag}(\mathbf{F}_k^1, \ldots, \mathbf{F}_k^F)$, $\mathcal{H}_k = \text{diag}(\mathbf{H}_k^1, \ldots, \mathbf{H}_k^F)$, $\mathbf{x}_s = [(\mathbf{x}_s^1)^T, \ldots, (\mathbf{x}_s^F)^T]^T$ and $\mathbf{n}_{sk} = [(\mathbf{n}_{sk}^1)^T, \ldots, (\mathbf{n}_{sk}^F)^T]^T$. To compute the CU transmit signal, a linear precoder is considered, that is the CU transmits

$$\mathbf{x}_s = \mathbf{V}_s \mathbf{d}_s, \quad (10)$$

where $\mathbf{V}_s \in \mathbb{C}^{M_s KFS_s KF}$, $\mathbf{d}_s = [\mathbf{d}_{sk}^{f_n}]_{1 \le k \le K, 1 \le f_n \le F} \in \mathbb{C}^{S_s KF}$ and $\mathbf{d}_{sk}^{f_n} \in \mathbb{C}^{S_s}$ denote the overall precoder computed at the CU, the concatenation of the K SBSs transmit symbols, $\mathbf{d}_{sk}^{f_n}$ is the SBS k

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transmit symbols, respectively. The transmit power at the CU is constrained to P_s, per subcarrier

$$tr(\mathbf{V}_s^{f_n^H}\mathbf{V}_s^{f_n}) \leq P_s, \tag{11}$$

The received signal after the filter matrix ($\mathbf{W}_k$) at the SUE_k by taking into account Eqs. (9) and (10) is

$$\mathbf{z}_{sk} = W_k(\mathcal{F}_k\mathbf{V}_m\mathbf{d}_m + \mathcal{H}_k\mathbf{V}_s\mathbf{d}_s + \mathbf{n}_{sk}). \tag{12}$$

3. Proposed approaches for precoder and filter matrix design

In this section, we present the design of precoder and filter matrices of the macro-cell and small-cell systems, in order to allow efficient coexistence of the two systems over the same radio spectrum. To design our proposed methods, we consider different levels of cooperation between the two systems. All the methods presented in this chapter are derived for a generic antenna configuration and therefore they are applicable for massive MIMO systems. On the other hand, the complexity will scale depending on the number of transmit antennas. Since the proposed methods involve matrix multiplications and inversions, thus the complexity will be similar to ZF-based precoding in massive MIMO. Moreover, for the sake of simplicity, we just consider one user per MBS but adding more macro-cell user will not impact the performance of both the systems, since interference can be completely removed. First, we summarize the methods presented in Ref. [23] for the case without SFBC. Then, we present in detail the proposed methods in Ref. [25], for the case where IA and SFBC are jointly used.

3.1. Methods without SFBC

In this section, we summarized the schemes presented in Ref. [23] for a general number of antennas at each terminal and for the case where OFDM modulation is considered. In Ref. [23], we design a new IA-based scheme for the considered heterogeneous systems. Namely, the coordinated $2n$-bit approach, which is an extension of the 2-bit method proposed in Ref. [24].

3.1.1. Full-coordinated scheme

For the full-coordinated method, we assume the knowledge of the $\mathbf{G}_1^{f_n}$ channel at the MBS. For the case where the MUE is equipped with single antenna, a maximal ratio transmission (MRT)-based precoder can be employed as in Ref. [24]. When an antenna array is used at the MUE, a ZF or MMSE-based precoders can be used. In this work, we consider the MRT-based precoder at the MBS given by

$$\mathbf{V}_m^{f_n} = \gamma_m \mathbf{G}_1^{f_n^H}, \tag{13}$$

Furthermore, we assumed that the macro-cell system is not aware of the existence of small-cell system within its coverage area and the MBS precoder $\mathbf{V}_m^{f_n}$ is fixed and it will not change due to the presence of SUEs. However, the SUEs can be severely affected by the macro-cell transmission. From Eqs. (1) and (4), we can see that to enforce the zero-interference condition and mitigate the interference coming from MBS, the filter matrix at SUE_k must satisfy

$$\mathbf{W}_k^{f_n}\mathbf{F}_k^{f_n}\mathbf{V}_m^{f_n} = 0, \tag{14}$$

From Eq. (14) it follows that to satisfy the zero-interference condition the filter matrix ($\mathbf{W}_k^{f_n}$) at SUEs is

$$\mathbf{W}_k^{f_n} = \text{null}(\mathbf{F}_k^{f_n}\mathbf{V}_m^{f_n}), \tag{15}$$

$$\mathbf{A}^{f_n} = \text{null}(\mathbf{V}_m^{f_n}). \tag{16}$$

Where $\mathbf{A}^{f_n}$ is the alignment direction that specifies completely the received macro-cell interfering signal towards the SUEs. Using this information, the small cells can align their transmission accordingly without experiencing any interference from the macro-cell system. It can be verified from the zero-interference condition mentioned in Eq. (14) that the DoF available for the small-cell system is $(N_s - N_m)K$.

3.1.2. Uncoordinated-static scheme

Once again for this scheme, we follow the same procedure (as for the previous method) to remove the interference from MBS at SUEs, but the precoder at MBS is static at the beginning of interaction between the two systems and it will remain constant, i.e. its value do not change every TTI and its value is also known at the small-cell terminals. Therefore, this method requires no inter-system cooperation. For example, we assume the precoder at MBS is the all-ones matrix, i.e. $\mathbf{V}_m^{f_n} = \mathbf{1}$ [23].

3.1.3. Coordinated 2n-bit scheme

To achieve a trade-off between performance and feedback requirements of the full-coordinated and uncoordinated-static methods, we propose a coordinated 2n-bit method. To design the alignment direction, we consider the same precoder used for the full-coordinated scheme. Only a quantized version of the alignment vector is exchanged between the two systems [23]. Therefore, we quantize the alignment direction with 2n bits (n bits for the real and n bits for the complex part, where $n = 1, 2, 3, ..$). The quantized alignment direction is

$$\mathbf{A}_q^{f_n} = f_Q(Re\{(\mathbf{A}^{f_n})\}) + jf_Q(Im\{(\mathbf{A}^{f_n})\}) \tag{17}$$

where $f_Q(.)$ denotes a quantization function, the $Re\{.\}$ and $Im\{.\}$ are the real and imaginary parts of alignment direction $\mathbf{A}^{f_n}$. In this chapter, for the sake of simplicity, we consider only uniform quantizers. Notice that for this case, the MBS precoder is also quantized, by taking into account the zero-interference condition ($\mathbf{A}_q^{f_n} = \text{null}(\mathbf{V}_{m,q}^{f_n})$), $\mathbf{V}_{m,q}^{f_n}$ is a quantized version of $\mathbf{V}_m^{f_n}$ [23].

3.2. Methods with SFBC

In this section, we design new joint IA and SFBC schemes without any information exchange between two systems as compared to the full-coordinated and coordinated 2n-bit methods,

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where we need the channel information $\mathbf{G}_1^f$ in order to design the precoder at the MBS and filter matrix at the SUEs. The main motivation behind the use of SFBC at the macro-cell system is that it allows the design of filter matrix at SUEs without having any coordination between the two systems. More specifically, the small-cells just need to sense that the macro-cell system is using an SFBC scheme [23].

3.2.1. IA-filter matrix design for methods with SFBC

Now, we present the design of IA-filter matrix at the SUEs for the proposed joint IA and SFBC scheme. We consider that the macro-cell system has no information about the existence of small-cells within its coverage area. In the coexistence scenario, the MBS interferes with the SUEs. From Eq. (12) we can find that to enforce the zero-interference condition and mitigate the interference coming from MBS, the IA-filter matrix at SUE_k must satisfy

$$\mathbf{W}_k \mathcal{F}_k \mathbf{V}_m = \mathbf{0}, \tag{18}$$

In order to cancel the interference coming from MBS towards the SUE_k, we need to compute an appropriate filter matrix at the SUE_k. From Eq. (18) it follows that to satisfy the zero-interference condition the IA-filter matrix at SUE_k is

$$\mathbf{W}_k = \text{null}(\mathcal{F}_k \mathbf{V}_m), \tag{19}$$

As mentioned in Section 2.2, the precoder $\mathbf{V}_m$ for SFBCs does not depend on the macro-channel and thus there is no need to exchange any information from the macro-cell to the small-cell system to design the IA-filter matrix, contrarily to the full-coordinated and coordinated $2n$-bit methods [23]. For these two cases, the precoder is computed for each channel instance and as the macro-cell terminal is a mobile terminal the equalizer matrix $\mathbf{W}_k$ must be computed on every TTI. This means that the IA-filter matrix must be exchanged between the two systems every TTI. Another possible strategy consists of estimating the equivalent channel $\mathbf{F}_k^{f_n}\mathbf{V}_m^{f_n}$, by listening to the pilot signals, but it will also require a high pilot density [29].

After applying the IA-filter matrix mentioned in Eq. (19) to Eq. (12), we obtain

$$\mathbf{z}_{sk} = \mathbf{W}_k(\mathcal{F}_k \mathbf{V}_m \mathbf{d}_m + \mathcal{H}_k \mathbf{V}_s \mathbf{d}_s + \mathbf{n}_{sk}) = \mathbf{W}_k \mathcal{H}_k \mathbf{V}_s \mathbf{d}_s + \mathbf{W}_k \mathbf{n}_{sk}. \tag{20}$$

From Eqs. (18) and (20) we verify that the interference from MBS is completely removed at SUEs. This is made possible due to the redundancy present in the MBS transmitted data symbols. Once again, for the joint IA and SFBC case due to the zero-interference condition mentioned in Eq. (18), the DoF available at the small-cells is $(N_s - N_m)K$.

3.2.1.1. Interference from small cells to macro-cell

In the previous section, we described how to tackle the interference from the macro- to the small cells. In this section, we describe how to cancel the interference from the small cells to the macro-cells (for all the methods presented in this chapter). Being a small-cell system it should not interfere with the macro-cell system (i.e. the macro-cell has priority to access the available resources). On the other hand, the SUEs should not interfere with each other. We consider that the SBSs are connected via the backhaul network (optical fibre) to a CU in order to perform joint processing of transmitted signals [25]. The CU has enough DoF (i.e. KM_s) to cancel both the interference that the SBSs cause in the MUE and the interference between SUEs. The precoding matrix at the CU is based on the ZF criteria, in order to zero force the macro-cell and small-cell channels together. In this context, the ZF precoder $\mathbf{V}_s^{f_n}$, computed at the CU, is given by Ref. [25]

$$\mathbf{V}_s^{f_n} = \mathbf{A}^{f_n^H}(\mathbf{A}^{f_n}\mathbf{A}^{f_n^H})^{-1}, f_n = 1, \ldots, F \tag{21}$$

where $\mathbf{A}^{f_n} = \mathbf{W}^{f_n}\mathbf{H}_{eq}^{f_n}$, $\mathbf{H}_{eq}^{f_n} = [(\mathbf{G}_2^{f_n})^H, (\mathbf{H}_1^{f_n})^H, \ldots, (\mathbf{H}_K^{f_n})^H]^H$ and $\mathbf{W}^{f_n} = diag(\mathbf{I}, \mathbf{W}_1^{f_n}, \ldots \mathbf{W}_k^{f_n}, \ldots \mathbf{W}_K^{f_n})$. The filter matrix $\mathbf{W}_k^{f_n}$ is known at the CU since the channels $\mathbf{F}_k^{f_n}$ are quasi-static, the SUEs may feedback them to the CU without much overhead requirements.

3.2.2. Examples for specific SFBC codes

In the following, we consider few examples of diversity-oriented SFBC schemes used at the macro-cell system in order to design the IA-filter matrix of our joint schemes. We considered three SFBC schemes: Alamouti codes [30], quasi-orthogonal codes [31] and Tarokh codes [32] with the data symbols coded in space and frequency as shown in **Figure 3**. Furthermore, from the context of space-time/space-frequency coding literature, the channel between adjacent carriers is assumed to be approximately constant,[3] i.e. $\mathbf{G}_1^{f_m} \approx \mathbf{G}_1^{f_n}, m \neq n \in \mathbb{N}$ [25].

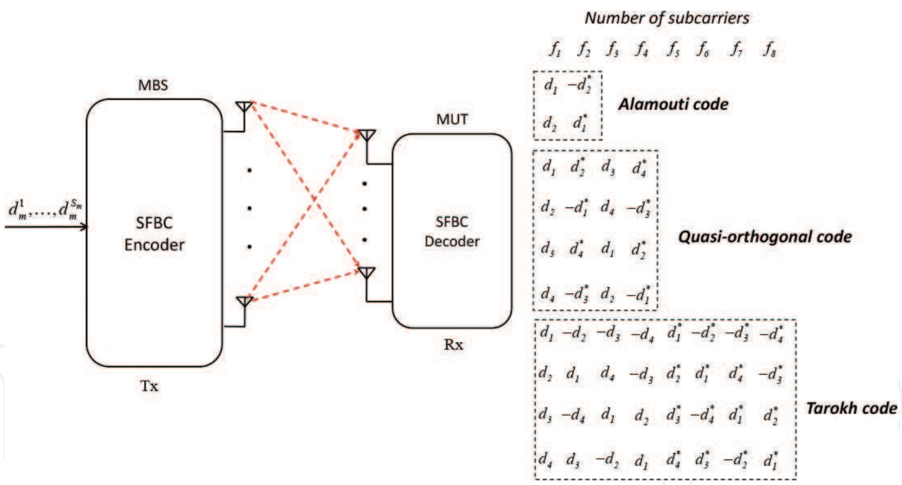

Figure 3. SFBC schemes at MBS.

- **Alamouti codes:** For the first case, we employ the standard Alamouti SFBC [30] based scheme at the MBS, with two ($M_m = 2$) antennas at the transmitter and single antenna ($N_m = 1$) at the receiver. For this well-known method, the encoder takes a block of two data symbols, i.e. d_1 and d_2. For a given subcarrier, two symbols are simultaneously

[3]OFDM-based systems are usually designed so that channels between some adjacent carriers are approximately flat.

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transmitted from the two antennas, as shown in **Figure 3**. For the first subcarrier f_1, the symbol transmitted from the first antenna is denoted by d_1 and from the second one by d_2 and over subcarrier f_2, $(-d_2)^*$ and $(d_1)^*$ are transmitted from the first and second antennas, respectively [23]. The transmitted signal at the MBS on subcarriers f_1 ($\mathbf{x}_m^{f_1}$) and f_2 ($\mathbf{x}_m^{f_2}$) is given by

$$\mathbf{x}_m^{f_1} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}, \mathbf{x}_m^{(f_2)^*} = \begin{bmatrix} -d_2 \\ d_1 \end{bmatrix} \tag{22}$$

For this case, as mentioned previously, the MBS precoder is applied jointly for $F = 2$ consecutive subcarriers as,

$$\mathbf{V}_m{}^T = \begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ j & 0 & 0 & j \\ 0 & j & -j & 0 \end{bmatrix} \tag{23}$$

As it can be verified from Eq. (23) the macro-cell precoder does not depend on the macro-channel, this means there is no need to exchange any channel information from the macro-cell to the small-cell system to design the IA-filter matrix.

- **Quasi-orthogonal codes:** As verified in Ref. [30], the Alamouti-based scheme is restricted to two antennas at the transmitter side. Therefore, we consider the quasi-orthogonal-based scheme that can be able to use more than two antennas at the transmitter and increase the multiplexing gain. For this case, the transmitter has four ($M_m = 4$) and the receiver has a single antenna ($N_m = 1$), as shown in **Figure 3**. In this method, four pairs of four data symbols are transmitted in parallel. The four data symbols are transmitted over four antennas on four subcarriers, $F = 4$ according to the following encoding [25]

$$\mathbf{x}_m^{f_1} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}, \mathbf{x}_m^{(f_2)^*} = \begin{bmatrix} d_2 \\ -d_1 \\ d_4 \\ -d_3 \end{bmatrix}, \mathbf{x}_m^{f_3} = \begin{bmatrix} d_3 \\ d_4 \\ d_1 \\ d_2 \end{bmatrix}, \mathbf{x}_m^{(f_4)^*} = \begin{bmatrix} d_4 \\ -d_3 \\ d_2 \\ -d_1 \end{bmatrix} \tag{24}$$

For this case, as mentioned previously, the MBS precoder is applied jointly for $F = 4$ consecutive subcarriers.

$$\mathbf{V}_m{}^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ j & 0 & 0 & 0 & 0 & j & 0 & 0 & 0 & 0 & j & 0 & 0 & 0 & 0 & j \\ 0 & j & 0 & 0 & -j & 0 & 0 & 0 & 0 & 0 & 0 & j & 0 & 0 & -j & 0 \\ 0 & 0 & j & 0 & 0 & 0 & 0 & j & j & 0 & 0 & 0 & 0 & j & 0 & 0 \\ 0 & 0 & 0 & j & 0 & 0 & -j & 0 & 0 & j & 0 & 0 & -j & 0 & 0 & 0 \end{bmatrix} \tag{25}$$

As seen in the Alamouti code, the macro-cell precoder for this case also does not depend on the macro-channel as verified from Eq. (25); this means there is no need to exchange any channel information from the macro-cell to the small-cell system to design the IA-filter matrix.

- **Tarokh codes:** Once again, for Tarokh codes we assume four antennas ($M_m = 4$) at the transmitter and a single antenna ($N_m = 1$) at the receiver side, as presented in **Figure 3**. The only difference is the number of subcarriers used to transmit the data symbols, for this case eight subcarriers are used, i.e. the Tarokh code that provides the code rate of 1/2. The four data symbols are transmitted over four antennas on eight subcarriers $F = 8$ according to the following encoding [25]

$$\mathbf{x}_m^{f_1} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}, \mathbf{x}_m^{f_2} = \begin{bmatrix} -d_2 \\ d_1 \\ -d_4 \\ d_3 \end{bmatrix}, \mathbf{x}_m^{f_3} = \begin{bmatrix} -d_3 \\ d_4 \\ d_1 \\ -d_2 \end{bmatrix}, \mathbf{x}_m^{f_4} = \begin{bmatrix} -d_4 \\ -d_3 \\ d_2 \\ d_1 \end{bmatrix}, \mathbf{x}_m^{(f_5)^*} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}, \mathbf{x}_m^{(f_6)^*} = \begin{bmatrix} -d_2 \\ d_1 \\ -d_4 \\ d_3 \end{bmatrix}, \\ \mathbf{x}_m^{(f_7)^*} = \begin{bmatrix} -d_3 \\ d_4 \\ d_1 \\ -d_2 \end{bmatrix}, \mathbf{x}_m^{(f_8)^*} = \begin{bmatrix} -d_4 \\ -d_3 \\ d_2 \\ d_1 \end{bmatrix} \tag{26}$$

For the Tarokh codes, the MBS precoder is applied jointly for $F = 8$ consecutive subcarriers as

$$\mathbf{V}_m{}^T = \left[\begin{array}{cccccccccccccccccccccccccccccccc} 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ j & 0 & 0 & 0 & 0 & j & 0 & 0 & 0 & 0 & j & 0 & 0 & 0 & 0 & j & -j & 0 & 0 & 0 & 0 & -j & 0 & 0 & 0 & 0 & -j & 0 & 0 & 0 & 0 & -j \\ 0 & j & 0 & 0 & -j & 0 & 0 & 0 & 0 & 0 & 0 & -j & 0 & 0 & -j & 0 & 0 & -j & 0 & 0 & j & 0 & 0 & 0 & 0 & 0 & 0 & j & 0 & 0 & -j & 0 \\ 0 & 0 & j & 0 & 0 & 0 & 0 & j & -j & 0 & 0 & 0 & 0 & -j & 0 & 0 & 0 & 0 & -j & 0 & 0 & 0 & 0 & -j & j & 0 & 0 & 0 & 0 & j & 0 & 0 \\ 0 & 0 & 0 & j & 0 & 0 & -j & 0 & 0 & j & 0 & 0 & -j & 0 & 0 & 0 & 0 & 0 & 0 & -j & 0 & 0 & j & 0 & 0 & -j & 0 & 0 & j & 0 & 0 & 0 \end{array}\right] \tag{27}$$

As seen for the quasi-orthogonal codes, the precoder is also constant and not dependent on the macro-cell channel as verified in Eq. (27), where this condition enables the design of the IA filter at SUEs without any information exchange between the two systems.

4. Performance versus information exchange comparison

As discussed in Section 3.1, the system achieves the best performance when full coordination is allowed between the two systems, i.e. the case with the full-coordinated scheme, where it requires the highest amount of information exchange, since the macro-cell system must share $2M_mN_m$ real numbers with small-cell terminals on every TTI. Considering an OFDM-based system, $2M_mN_mN_c$ real number increases the feedback constraints. No information exchange is required for the uncoordinated-static method but this scheme results in worst performance for the macro-cell system. To overcome the limitations of full-coordinated and uncoordinated-static schemes and to achieve a good balance between performance and information exchange, we designed a coordinated $2n$-bit approach [23] that results in reduced information exchange requirements and achieves quite close to the optimal performance. Furthermore, the proposed joint IA and SFBC scheme [25] that has the same information exchange requirement as uncoordinated-static scheme provides much better performance as compared to the uncoordinated-static method. **Table 1** summarizes the information exchange requirements and performance of the proposed methods.

Methods	Information-exchange requirements	Performance
Full-coordinated	$2M_mN_mN_c$ Real number	Optimal performance
Uncoordinated-static	0	Worst performance
Coordinated 2n-bit	$2nM_mN_mN_c$ bits	Close to optimal
Joint IA and SFBC scheme	0	Much better than uncoordinated-static method

Table 1. Comparison of inter-system information exchange and performance.

5. Numerical results and discussion

This section provides the performance assessment of all the methods presented in this chapter. We compare the joint IA and SFBC methods to the full-coordinated, uncoordinated-static and coordinated 2n-bit schemes with the help of numerical simulations. Furthermore, for the coordinated 2n-bit scheme, we just consider $n = 1$ to compare the results for macro- and small-cell systems. As it will be seen from the numerical results, the coordinated 2-bit scheme almost provides close to the optimal performance for both the macro-cell and the small-cell systems, which means that by using $n > 1$ the additional performance improvement will be marginal. To perform our simulations, we consider two small-cells (i.e. $K = 2$) sharing the spectrum with macro-cell, since we can completely mitigate the interference irrespective the number of small cells, adding more small cells will not impact the performance of the macro-cell system. Furthermore, the SBSs are able to cooperate through a backhaul network to a CU to perform joint processing of signals. We consider two scenarios:

- Scenario 1: The number of antennas at the MBS, SBSs and SUEs is 2 and single antenna at the MUE, i.e. $M_m = M_s = N_s = 2$, $N_m = 1$.
- Scenario 2: The number of antennas at the MBS, SBSs and SUEs is 4 and 1 at the MUE, i.e. $M_m = M_s = N_s = 4$, $N_m = 1$.

We consider the ITU pedestrian channel model B, with modified tap delays according to the sampling frequency specified in LTE standards. The SNR at the cell edge is defined as (P_t/σ^2), where P_t is the transmit power. For the macro-cell, the transmit power is equal to $P_m = 1$ and for the small cells it is equal to $P_s = 1$. We used the following OFDM parameters used for simulating both the macro-cell and small-cell systems: FFT size = 1024 (where only 128 subcarriers are used for both the systems); sampling frequency $f_s = 15.36$MHz; cyclic prefix length $c_p = 5.21\mu$s and subcarrier separation is 15 kHz [23]. We present results for full-coordinated, coordinated 2-bit, uncoordinated-static and three joint IA and SFBCs: IA with a standard Alamouti code [30], IA with a quasi-orthogonal code [31] and IA with a half-rate orthogonal Tarokh code [32]. In order to allow an appropriate comparison, all the considered methods are evaluated for the same spectral efficiency. Therefore, we used QPSK modulation for joint IA and Alamouti code, joint IA and quasi-orthogonal code, coordinated 2-bit, full-coordinated and uncoordinated-static schemes and 16-QAM for the joint IA and Tarokh codes.

Let us start by considering the first scenario, where IA is jointly used with Alamouti code. For this case, we compare the performance of full-coordinated (for both the case of macro-cell/

small-cell coexistence and the case where small-cell system is switched off), coordinated 2-bit, uncoordinated-static and joint IA and Alamouti code schemes. As it can be seen from **Figure 4**, the performance of the coordinated 2-bit approach is quite close to the optimal performance. The BER performance of the joint IA and Alamouti code approach has a gap of around 3 dB as compared to the full-coordinated case, since the SFBC scheme can provide an array gain of 1 [23]. On the other hand, the joint IA and Alamouti scheme provides much better performance (a gap of around 10 dB for a target BER of 10^{-3}) as compared to the uncoordinated-static method while the information-exchange requirements for both schemes are identical.

In **Figure 5**, we present the BER curve of the first scenario for the small-cell system. In **Figure 5**, we just consider the curves for the full-coordinated (as the performance of full-coordinated, coordinated 2-bit and uncoordinated-static methods is identical) and the joint IA and Alamouti

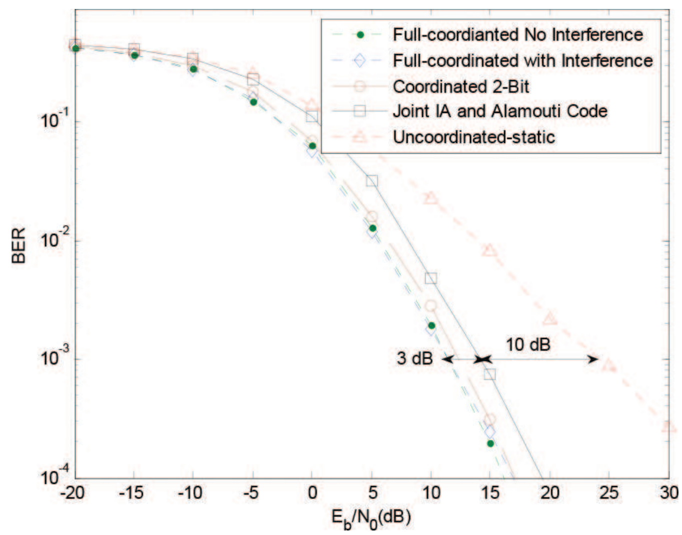

Figure 4. BER performance for the macro-cell system (scenario 1).

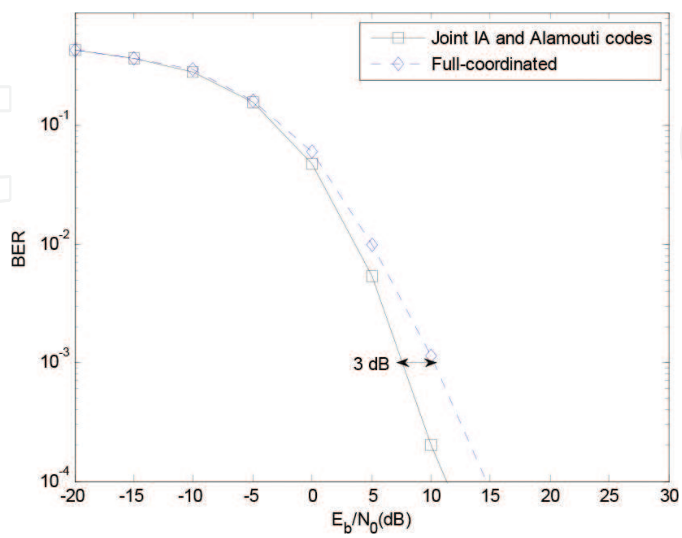

Figure 5. BER performance for the small-cell system (scenario 1).

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code scheme. This is true, since the design of filter matrix is not dependent on the small-cell channels $[\mathbf{H}_k^f]_{1\le k\le K}$. Therefore, the equivalent channel preserves the original channel distribution. As seen from **Figure 5**, the joint IA and Alamouti code provides 3 dB which is a better performance as compared to the full-coordinated approach. This is due to the fact that for the SFBC scheme every symbol is transmitted over two subcarriers, contrarily to the full-coordinated method where each symbol only spans one subcarrier [23].

Let us now consider the second scenario where IA is combined with the quasi-orthogonal and Tarokh codes. For this case, we compare the performance of the full-coordinated (for both the case of macro-cell/small-cell coexistence and the case where small-cell system is switched off), coordinated 2-bit, uncoordinated-static, joint IA and quasi-orthogonal code and joint IA and Tarokh code methods. Figures 6 and 7 present the BER performance for the macro-cell and small-cell system, respectively (using QPSK modulation for full-coordinated, coordinated 2-bit uncoordinated-static and joint IA and quasi-orthogonal code curves and 16-QAM modulation for the joint IA and Tarokh code curve). As seen in **Figure 6**, we can notice that the coordinated 2-bit approach provides close to optimal performance. On the other hand, the performance of joint IA and quasi-orthogonal code, joint IA and Tarokh code methods has a gap of around 5 and 3 dB, respectively, as compared to the full-coordinated method and achieves much better performance (a gap of around 14 and 18 dB for a target BER of 10^{-3}) as compared to the uncoordinated-static scheme, even if the information-exchange requirements of these schemes are identical.

In **Figure 7**, we compare the BER performance of the proposed joint IA and quasi-orthogonal code and joint IA and Tarokh code with the full-coordinated method for the small-cell system. The proposed joint IA and quasi-orthogonal code scheme provides around 3 dB better performance as compared to the case where full coordination is allowed between the two tiers. The performance of the proposed joint IA and Tarokh code scheme is around 1 dB which is better as compared to the full-coordinated case.

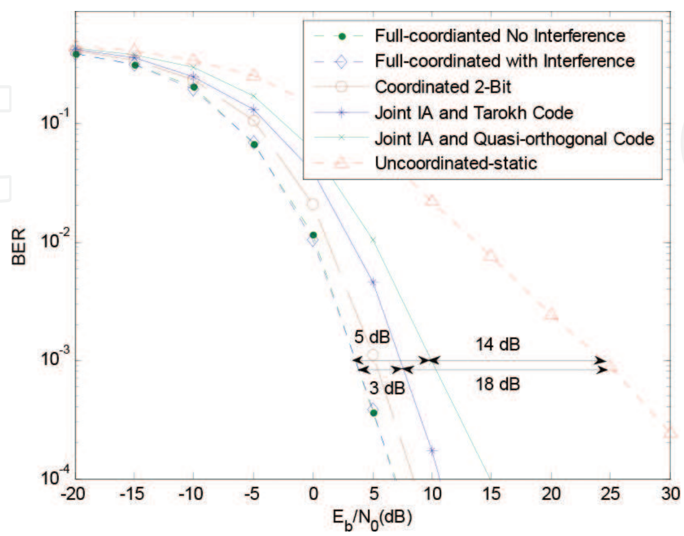

Figure 6. BER performance for the macro-cell system (scenario 2).

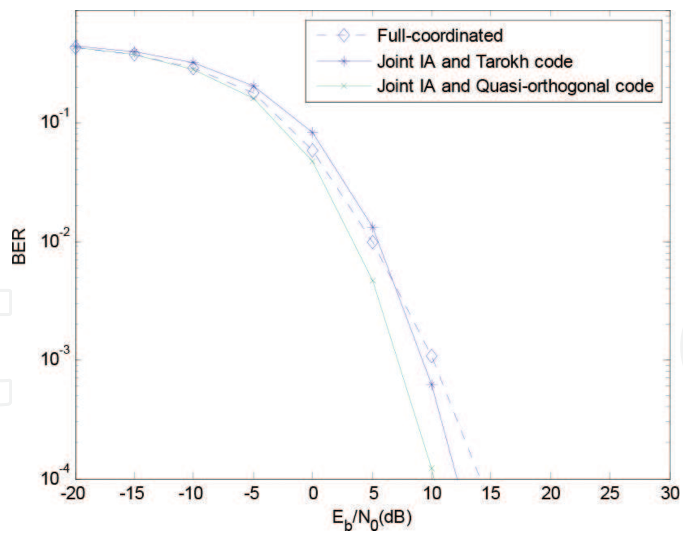

Figure 7. BER performance for the small-cell system (scenario 2).

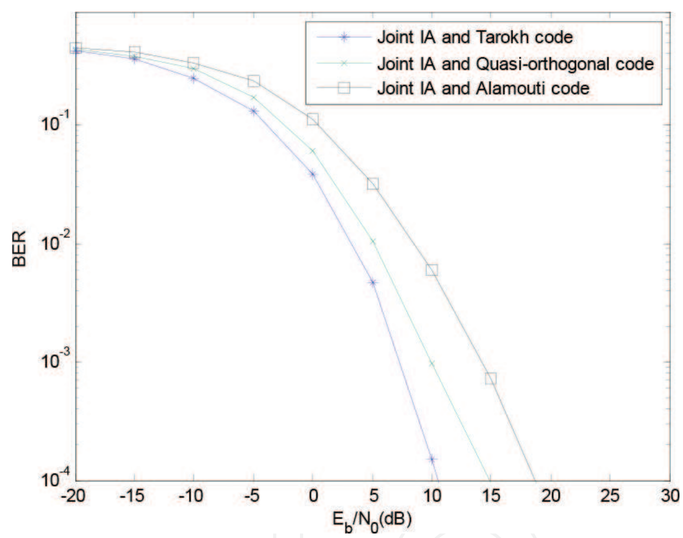

Figure 8. BER performance at the macro-cell system for joint IA and Alamouti code/joint IA and quasi-orthogonal code/ joint IA and Tarokh code.

In **Figures 8** and **9**, we compare the performance of SFBC schemes at the macro-cell and small-cell systems, respectively. As it can be seen from Figure 8, the joint IA and Tarokh code provides the best performance as compared to the joint IA and Alamouti code/quasi-orthogonal code (i.e. a gap of around 3 and 6dB, respectively). At the small-cell system, the performance of joint IA and Alamouti code/joint IA and quasi-orthogonal code is identical and the performance of joint IA and Tarokh code is around 2 dB which is worse as compared to the other two schemes, as shown in Figure 9. This is due to the fact that the high order modulation (16-QAM) is used for the joint IA and Tarokh code and therefore it is more prone to errors than the other two SFBC schemes that use QPSK modulation.

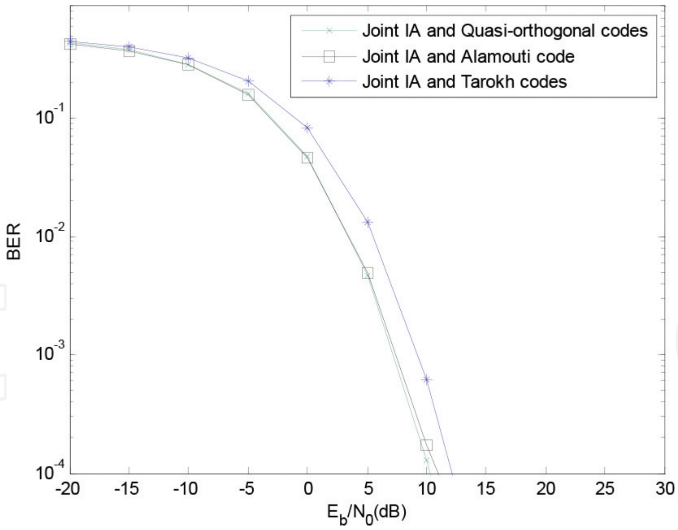

Figure 9. BER performance at small-cell system for joint IA and Alamouti code/joint IA and quasi-orthogonal code/joint IA and Tarokh code.

6. Conclusions

In this chapter, we presented a general framework of our previously proposed methods for the downlink of heterogeneous-based systems. The system achieves the best performance with full-coordinated scheme, but with very high feedback requirements. For the uncoordinated-static approach, it requires no information exchange between the two systems, but the performance of the macro-cell system is degraded. To overcome the limitations of full-coordinated and the uncoordinated-static methods, we designed the coordinated $2n$-bit scheme and the joint IA and SFBC method that can be applied to any SFBC.

The proposed joint IA and SFBC scheme allows the small-cell system to opportunistically access the free space resources of the macro-cell system without any performance degradation. The proposed joint IA and SFBC method also provides much improved performance with comparable information-exchange requirements to the uncoordinated-static approach. We can say that the proposed method allows the network to achieve the benefits of full-coordinated and uncoordinated-static methods without their main drawbacks. As one of the requirements of 5G is to increase spectral efficiency by a factor about 10, the proposed method will contribute to this goal and thus it can be very useful for the future 5G-based networks.

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Author details

Syed Saqlain Ali*, Daniel Castanheira, Adão Silva and Atílio Gameiro

*Address all correspondence to: syedsaqlain@av.it.pt

Instituto de Telecomunicações, University Campus, Aveiro, Portugal

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