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Concepts for coordinated multipoint and distributed beamforming using FBMC

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Abstract:

This document shortly summarizes the main concepts that will be presented in deliverable D6.2. The issue of coordinated beamforming design for distributed multi-user MIMO systems using FBMC/OQAM is investigated. New methods are developed to alleviate the dimensionality constraint imposed on the number of antennas in state-of-the art solutions. Both cases of full coordination and partial coordination are considered. Furthermore, solutions are also investigated for highly selective channels where other methods, which are based on the usual assumption of an approximatively flat channel across subcarriers, fail to provide satisfactory results. Finally, the related issue of preamble-based MIMO channel estimation is investigated for synchronized and unsynchronized scenarios.

Document Revision History

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1.1	08/12/2014	Jerome Louveaux (UCL),Yao Cheng (ITU), Martin Haardt (ITU), Yahia Medjahdi (UCL), Francois Rottenberg (UCL)	Update of state-of-the art (section 2) and section 4

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1. Introduction

The objective of this report is to focus on how multi-user MIMO strategies, and in particular coordinated multi-point (CoMP) and distributed beamforming techniques, can be applied in a PMR scenario using FBMC/OQAM modulation. It presents a short summary of the main concepts that will be developed in D6.2. For more detailed mathematical derivations and simulation results, please refer to deliverable D6.2.

Filter bank based multi-carrier modulation (FBMC) is widely known as a promising alternative to orthogonal frequency division multiplexing with the cyclic prefix insertion (CP-OFDM). Thanks to the use of spectrally well-contained synthesis and analysis filter banks at the transmitter and at the receiver [1], [2], FBMC features a concentrated spectrum and a much lower out-of-band radiation compared to CP-OFDM. Consequently, it is beneficial to choose FBMC over CP-OFDM for asynchronous scenarios [3], [4], or to achieve an effective utilization of spectrum holes [5], [6]. It is also widely known however that the implementation of several MIMO techniques, which are fairly simple in CP-OFDM systems, can become much more complex when using the FBMC/OQAM modulation, due to the so-called *intrinsic interference*. This has been an important issue investigated in the literature in the last years. For instance, [7] and [8] have developed receive processing techniques for multiple-input-multiple-out (MIMO) FBMC/OQAM systems, when it is assumed that the channel frequency responses of adjacent subcarriers do not vary. On the other hand, to the best of our knowledge, most of the FBMC/OQAM related literature has focused on the centralized scenario where all the (downlink) transmitting antennas are collocated at a single base-station. However in the context of CP-OFDM, the coordinated multi-point (CoMP) technique is known as one of the advanced communication techniques that are able to provide benefits of reduced intercell interference and enhanced cell edge throughput. It has generated a very fruitful research [9], [10], [11], [12], [13]. It is therefore important to investigate the corresponding scenario for FBMC/OQAM-based systems and identify if efficient algorithms can also be designed to benefit from the same advantages.

In this report, we focus on downlink CoMP and the schemes that belong to the category of joint transmission [9]. When the full cooperation between the base stations of adjacent cells is assumed, the channel state information (CSI) and signals for all users are shared by the base stations. In this case, a virtual multi-user MIMO downlink setting is formed, where the transmit antennas are geographically separated. Thereby, the transmission strategies that have been developed for the single cell multi-user MIMO downlink can be employed. Nevertheless, such a full cooperation scheme is not practical due to issues such as it requires excessive information exchange resulting in a large signaling overhead, and the CSI of all users is very hard to acquire [11]. As a more realistic solution, partial cooperation schemes have been proposed in [11], [12], [14], where the users are classified into two categories, cell [or in some papers [11], [12] cluster that consists of multiple cells] interior users and cell (cluster) edge users. The base stations of adjacent cells (clusters) transmit the same signals to the cell (cluster) edge users, and coordinated beamforming techniques that rely on the limited cooperation between the cells (clusters) (e.g., the exchange of the beamforming matrices for cell (cluster) edge users) are employed to suppress the intra-cell (cluster) and inter-cell (cluster) interference. For these downlink CoMP scenarios, it is more likely that the total number of receive antennas of the users served by one base station is larger than the number of transmit antennas. Thus, transmission strategies that are able to tackle such a case are required. Note that in the aforementioned publications on CP-OFDM based downlink CoMP, perfect synchronization is assumed. However, the asynchronous nature of the interference in the downlink CoMP setting

is emphasized in [15]. It has been shown in [15] that the lack of perfect synchronization causes a performance degradation. Such a fact greatly motivates the use of FBMC as a replacement of CP-OFDM, as FBMC is more robust against synchronization errors compared to CP-OFDM. On the other hand, FBMC/OQAM-based downlink CoMP is less robust to the channel frequency selectivity and methods need to be designed in order to deal with this issue.

Based on all these considerations, D6.2 will focus on 3 main issues related to the implementation of downlink CoMP in FBMC/OQAM-based systems:

- The design of beamforming schemes that cope with the intrinsic interference in a mildly frequency selective channels, taking particular care of the case where the total number of receive antennas of the different users served is larger or equal to the total number of transmit antennas (section 2).

- The design of beamforming schemes for a highly frequency selective channel (section 3).

- The estimation of the distributed downlink MIMO channel taking into account the imperfect synchronization (section 4).

The main concepts used to solve these issues are described below. The more detailed results will be presented in deliverable D6.2.

2. Intrinsic interference mitigating coordinated beamforming (IIM-CBF) for the downlink of FBMC/OQAM based multi-user MIMO systems and coordinated multi-point systems

A few strategies for multiuser MIMO downlink transmission with FBMC/OQAM modulation have already been presented in the literature. A zero forcing (ZF) based approach has been proposed in [16] for multi-stream transmissions in a MIMO FBMC/OQAM system where the channel is not restricted to flat fading. More details of the performance analysis of this algorithm have been presented in [17]. However, the work in [16] and [17] is limited to the case where the number of receive antennas does not exceed the number of transmit antennas. This is easily understood from the degrees of freedom that are required to impose the absence of interference between different streams to different users. In addition, the authors have shown numerically and have also pointed out that their proposed approach only provides a satisfactory performance in an asymmetric configuration, i.e., when the number of transmit antennas is strictly larger than the number of receive antennas. Based on the concept of mitigating the intrinsic interference mentioned above for point-to-point MIMO FBMC/OQAM systems, the authors in [18] have adapted the conventional spatial Tomlinson Harashima precoder (STHP) to an FBMC/OQAM based multiple-input-single-output broadcast channel (MISO-BC) which results in a new non-linear precoder. It is known that non-linear precoders have a higher computational complexity compared to linear precoders. Moreover, the non-linear precoding technique in [18] is restricted to the case where each user is equipped with only a single receive antenna. On the other hand, a block diagonalization (BD) based linear precoder has been developed in [19] for the FBMC/OQAM based multi-user MIMO downlink with space division multiple access (SDMA). It adopts the central idea of BD [20] to mitigate the multi-user interference and then uses the ZF based approach [16] to deal with the intrinsic interference cancellation for the resulting equivalent single-user transmissions. Consequently, this algorithm inherits the drawback of the ZF based scheme such that it also fails to achieve a good performance in a symmetric multi-user MIMO downlink setting, where the number of transmit antennas at the base station is equal to the total number of receive antennas of the users. In addition, this linear precoder suffers from the dimensionality constraint that the total number of receive antennas of the users must not exceed the number of transmit antennas at the base station.

In this section, we investigate intrinsic interference mitigating coordinated beamforming (IIM-CBF) based transmission strategies for the downlink of multi-user MIMO systems and coordinated multi-point (CoMP) systems where filter bank based multi-carrier with offset quadrature amplitude modulation (FBMC/OQAM) is employed. Our goal is to alleviate the dimensionality constraint imposed on the state-of-the-art solutions for FBMC/OQAM based space division multiple access (SDMA) that the total number of receive antennas of the users must not exceed the number of transmit antennas at the base station. First, a single-cell multi-user MIMO downlink system is considered, and two IIM-CBF algorithms are proposed for the case where the number of transmit antennas at the base station is equal to the total number of receive antennas of the users and the case where the former is smaller than the latter, respectively. The central idea is to jointly and iteratively calculate the precoding matrix and the decoding matrix for each subcarrier to mitigate the multi-user interference as well as the intrinsic interference inherent in FBMC/OQAM based systems. Second, for a CoMP downlink scenario where partial coordination among the base stations is considered, the application of coordinated beamforming based transmission schemes is further investigated. An appropriate IIM-CBF technique is

proposed.

Note that similarly to current literature, we focus on scenarios where the channel on each subcarrier is flat fading in this section. However, we will consider more critical downlink settings of multi-user PMR scenarios where the channels exhibit severe frequency selectivity in section 3. In addition, in the aforementioned publications on the FBMC/OQAM based multi-user downlink, the impact of the residual carrier frequency offsets (CFOs) has not been investigated. In deliverable D6.2, the effects of the residual CFOs will be investigated and will demonstrate the superiority of the FBMC/OQAM based system over its CP-OFDM based counterpart in the tolerance of the synchronization errors. Channel knowledge (CSI) is always assumed in this section. The channel estimation issue is investigated in section 4. Some results for imperfect channel estimations in similar scenarios have been investigated in D4.3.

In order to present the various solutions investigated, we briefly present the system model of a single-cell multi-user MIMO FBMC/OQAM system. Two state-of-the-art transmission strategies for such a system are reviewed. Then, we describe the two proposed algorithms IIM-CBF 1 and IIM-CBF 2 for the case where the number of transmit antennas at the base station is equal to the total number of receive antennas of the users and the case where the former is smaller than the latter, respectively. With our focus on the CoMP downlink, we further present another coordinated beamforming based transmission scheme, namely "IIM-CBF 3".

2.1   System model and state-of-the-art solutions

In a multi-user MIMO downlink system where SDMA is employed, one base station equipped with $M_{\mathrm{T}}^{(\mathrm{BS})}$ transmit antennas transmits to Q users at the same time and on the same frequency. The number of receive antennas of the qth user is denoted by M_{R_q}, and the total number of receive antennas of all users severed simultaneously is then $M_{\mathrm{R}}^{(\mathrm{tot})} = \sum_{q=1}^{Q} M_{\mathrm{R}_q}$. Assuming that the channel on each subcarrier can be treated as flat fading [16], [17], [19], the combined receive vector on the kth subcarrier and at the nth time instant is denoted by $\boldsymbol{y}_k[n] = \begin{bmatrix} \boldsymbol{y}_{1,k}^{\mathrm{T}}[n] & \boldsymbol{y}_{2,k}^{\mathrm{T}}[n] & \cdots & \boldsymbol{y}_{Q,k}^{\mathrm{T}}[n] \end{bmatrix}^{\mathrm{T}} \in \mathbb{C}^{M_{\mathrm{R}}^{(\mathrm{tot})}}$ where the received signals of all Q users are stacked and can be represented by

$$\boldsymbol{y}_k[n] = \boldsymbol{H}_k[n]\boldsymbol{F}_k[n]\boldsymbol{d}_k[n] + \sum_{i=n-3}^{n+3}\sum_{\ell=k-1}^{k-+1} \boldsymbol{H}_\ell[i]\boldsymbol{F}_\ell[i]c_{i\ell}\boldsymbol{d}_\ell[i]$$
$$+ \boldsymbol{n}_k[n], \quad (\ell,i) \neq (k,n). \tag{2.1}$$

Here $\boldsymbol{H}_k[n] \in \mathbb{C}^{M_{\mathrm{R}}^{(\mathrm{tot})} \times M_{\mathrm{T}}^{(\mathrm{BS})}}$ denotes the combined channel matrix of all Q users[1] and is written as

$$\boldsymbol{H}_k[n] = \begin{bmatrix} \boldsymbol{H}_{1,k}^{\mathrm{T}}[n] & \boldsymbol{H}_{2,k}^{\mathrm{T}}[n] & \cdots & \boldsymbol{H}_{Q,k}^{\mathrm{T}}[n] \end{bmatrix}^{\mathrm{T}}, \tag{2.2}$$

where $\boldsymbol{H}_{q,k}[n] \in \mathbb{C}^{M_{\mathrm{R}_q} \times M_{\mathrm{T}}^{(\mathrm{BS})}}$ represents the channel frequency response between the base station and the qth user, $q = 1, 2, \ldots, Q$. The data vector $\boldsymbol{d}_k[n] \in \mathbb{R}^d$ with the total number of spatial streams $d = \sum_{q=1}^{Q} d_q$ is expressed as

$$\boldsymbol{d}_k[n] = \begin{bmatrix} \boldsymbol{d}_{1,k}^{\mathrm{T}}[n] & \boldsymbol{d}_{2,k}^{\mathrm{T}}[n] & \cdots & \boldsymbol{d}_{Q,k}^{\mathrm{T}}[n] \end{bmatrix}^{\mathrm{T}}, \tag{2.3}$$

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[1]Here we only provide the formulas of the channel matrices, precoding matrices, and data vectors on the kth subcarrier and at the nth time instant explicitly due to limited space. In case of the ℓth subcarrier and the ith time instant, the corresponding expressions can be obtained by replacing k and n with ℓ and i, respectively.

where $\boldsymbol{d}_{q,k}[n] \in \mathbb{R}^{d_q}$ denotes the desired signal for the qth user on the kth subcarrier and at the nth time instant when $(k+n)$ is even[2], and d_q denotes the number of spatial streams sent to the qth user. The terms $c_{i\ell}\boldsymbol{d}_\ell[i]$ in (2.1) contribute to the intrinsic interference and are pure imaginary if the prototype pulse satisfies the perfect reconstruction property [21], [18], where $\ell = k-1,\ k,\ k+1,\ i = n-3,\ldots,n+3$, and $(\ell, i) \neq (k, n)$. The coefficients $c_{i\ell}$ (cf. Table 2-1) represent the system impulse response determined by the synthesis and analysis filters. The PHYDYAS prototype filter [22] is used, and the overlapping factor is chosen to be $K = 4$. For more details about FBMC/OQAM systems, the reader is referred to [21]. Moreover, $\boldsymbol{n}_k[n] \in \mathbb{C}^{M_{\mathrm{R}}^{(\mathrm{tot})}}$ denotes the combined additive white Gaussian noise vector with variance σ_n^2, and the noise is assumed to be spatially uncorrelated. For the qth user, the noise autocorrelation matrix is written as $\sigma_n^2 \boldsymbol{I}_{M_{\mathrm{R}_q}}$.

	$n-3$	$n-2$	$n-1$	n	$n+1$	$n+2$	$n+3$
$k-1$	$0.043\jmath$	-0.125	$-0.206\jmath$	0.239	$0.206\jmath$	-0.125	$-0.043\jmath$
k	-0.067	0	0.564	1	0.564	0	-0.067
$k+1$	$-0.043\jmath$	-0.125	$0.206\jmath$	0.239	$-0.206\jmath$	-0.125	$0.043\jmath$

Table 2-1: Coefficients $c_{i\ell}$ representing the system impulse response determined by the synthesis and analysis filters [21] (the PHYDYAS prototype filter [22] used with the overlapping factor $K = 4$)

Furthermore, $\boldsymbol{F}_k[n] \in \mathbb{C}^{M_{\mathrm{T}}^{(\mathrm{BS})} \times d}$ contains the precoding matrices for all users

$$\boldsymbol{F}_k[n] = \begin{bmatrix} \boldsymbol{F}_{1,k}[n]\boldsymbol{G}_{1,k}[n] & \boldsymbol{F}_{2,k}[n]\boldsymbol{G}_{2,k}[n] & \cdots & \boldsymbol{F}_{Q,k}[n]\boldsymbol{G}_{Q,k}[n] \end{bmatrix}, \qquad (2.4)$$

where, in many approaches as explained below, the precoding for user q can be factorized into two matrices $\boldsymbol{F}_{q,k}[n] \in \mathbb{C}^{M_{\mathrm{T}}^{(\mathrm{BS})} \times M_{\mathrm{T}_q}^{(\mathrm{eq})}}$, and $\boldsymbol{G}_{q,k}[n] \in \mathbb{C}^{M_{\mathrm{T}_q}^{(\mathrm{eq})} \times d_q}$.

In some publications on MIMO FBMC/OQAM systems, such as [7] and [8], it is assumed that the channel stays constant across adjacent subcarriers and during consecutive symbol periods. Consequently, transmission strategies that have been developed for multi-user MIMO CP-OFDM downlink systems can be straightforwardly extended to their FBMC/OQAM based counterparts where only one additional step is required, i.e., taking the real part of the resulting signal after the multiplication by the decoding matrix

$$\hat{\boldsymbol{d}}_k[n] = \mathrm{Re}\left\{ \boldsymbol{D}_k^{\mathrm{H}}[n]\boldsymbol{y}_k[n] \right\}, \qquad (2.5)$$

where $\boldsymbol{D}_k[n] \in \mathbb{C}^{M_{\mathrm{R}}^{(\mathrm{tot})} \times d}$ is the combined block-diagonal decoding matrix on the kth subcarrier and at the nth time instant that contains the decoding matrices $\boldsymbol{D}_{q,k}[n] \in \mathbb{C}^{M_{\mathrm{R}_q} \times d_q}$, $q = 1, 2, \ldots, Q$, for the Q users, respectively. Here $\mathrm{Re}\{\cdot\}$ symbolizes the real part of the input argument, while $\mathrm{Im}\{\cdot\}$ represents the imaginary part. This simple scheme relies on the impractical assumption that the channel is flat fading and time invariant. In case of frequency

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[2]For the case where $(k+n)$ is odd, the desired signal on the kth subcarrier and at the nth time instant is pure imaginary, while the intrinsic interference is real providing that the prototype pulse satisfies the perfect reconstruction property [21], [18]. As the two cases are essentially equivalent to each other, we only take the case where $(k+n)$ is even to describe the proposed algorithm in this document. In addition, each entry in the data vector corresponds to either the in-phase component or the quadrature component of a QAM symbol that is assumed to have unit energy.

selective channels, this transmission strategy fails to eliminate the intrinsic interference inherent in FBMC/OQAM systems and thus quickly suffers from a performance degradation. In contrast, most other methods try to eliminate this intrinsic interference and are thus less sensitive to channel frequency selectivity (even if they assume approximately flat channels inside subcarriers).

In [19] a BD based precoding algorithm has been proposed for FBMC/OQAM based multi-user MIMO downlink systems, where $M_{\mathrm{T}}^{(\mathrm{BS})} \geq M_{\mathrm{R}}^{(\mathrm{tot})}$. First, the BD algorithm [20] is used to calculate the first part of the precoding matrix $\boldsymbol{F}_{q,k}[n]$, $q = 1, 2, \ldots, Q$, for the Q users to mitigate the multi-user interference. Then, the ZF based method is employed on each equivalent single-user transmission to suppress the intrinsic interference. This approach outperforms the straightforward extension of the CP-OFDM case in the sense that it is able to tolerate a certain level of the frequency selectivity of the channel. However, it suffers from the dimensionality constraint that the number of transmit antennas at the base station has to be larger than or equal to the total number of receive antennas of the users, i.e., $M_{\mathrm{T}}^{(\mathrm{BS})} \geq M_{\mathrm{R}}^{(\mathrm{tot})}$. For the case where $M_{\mathrm{T}}^{(\mathrm{BS})} = M_{\mathrm{R}}^{(\mathrm{tot})}$, this scheme is not able to provide a satisfactory performance.

2.2 Coordinated beamforming for the single-cell multi-user MIMO downlink

Based on the philosophy on the precoding design for multi-user MIMO downlink settings first proposed in [23], the precoding matrix for each user is decomposed into two parts as already shown in (2.4). For the qth user, the first part $\boldsymbol{F}_q$ eliminates the multi-user interference[3]. The second part $\boldsymbol{G}_q$ plays the role of the transmit beamforming matrix for each equivalent single-user transmission after the multi-user interference cancellation. Due to the fact that the intrinsic interference resides in FBMC/OQAM based systems, we propose to further decouple $\boldsymbol{G}_q$ into two parts, i.e.,

$$\boldsymbol{G}_q = \boldsymbol{G}_{q,1}\boldsymbol{G}_{q,2} \in \mathbb{C}^{M_{\mathrm{T}_q}^{(\mathrm{eq})} \times d_q}, \tag{2.6}$$

where $\boldsymbol{G}_{q,1} \in \mathbb{C}^{M_{\mathrm{T}_q}^{(\mathrm{eq})} \times M_{x_q}}$ is computed to suppress the intrinsic interference, and $\boldsymbol{G}_{q,2} \in \mathbb{R}^{M_{x_q} \times d_q}$ is used for the spatial mapping.

2.2.1 The IIM-CBF 1 algorithm

We first propose a coordinated beamforming based transmission scheme IIM-CBF 1 for symmetric multi-user MIMO downlink settings where $M_{\mathrm{T}}^{(\mathrm{BS})} = M_{\mathrm{R}}^{(\mathrm{tot})}$. BD [20] is employed to calculate the first part of the precoding matrices $\boldsymbol{F}_q \in \mathbb{C}^{M_{\mathrm{T}}^{(\mathrm{BS})} \times M_{\mathrm{T}_q}^{(\mathrm{eq})}}$, $q = 1, 2, \ldots, Q$. For the qth user, define a matrix $\widetilde{\boldsymbol{H}}_{\mathrm{e}} \in \mathbb{C}^{(M_{\mathrm{R}}^{(\mathrm{tot})} - M_{\mathrm{R}_q}) \times M_{\mathrm{T}}^{(\mathrm{BS})}}$ as

$$\widetilde{\boldsymbol{H}}_{\mathrm{e}} = \left[\begin{array}{ccccccc} \boldsymbol{H}_1^{\mathrm{T}} & \cdots & \boldsymbol{H}_{q-1}^{\mathrm{T}} & \boldsymbol{H}_{q+1}^{\mathrm{T}} & \cdots & \boldsymbol{H}_Q^{\mathrm{T}} \end{array} \right]^{\mathrm{T}}, \tag{2.7}$$

which contains the channel matrices of all the other users. The precoding matrix $\boldsymbol{F}_q$ for the qth user is obtained as $\boldsymbol{F}_q = \widetilde{\boldsymbol{V}}_{\mathrm{e}(q,0)} \in \mathbb{C}^{M_{\mathrm{T}}^{(\mathrm{BS})} \times M_{\mathrm{T}_q}^{(\mathrm{eq})}}$, where $\widetilde{\boldsymbol{V}}_{\mathrm{e}(q,0)}$ contains the last $M_{\mathrm{T}_q}^{(\mathrm{eq})}$ right singular vectors that form an orthonormal basis for the null space of $\widetilde{\boldsymbol{H}}_{\mathrm{e}}$ [20]. The resulting

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[3]In IIM-CBF 3 for the CoMP downlink, $\boldsymbol{F}_q$ suppresses both the intra-cell interference and the inter-cell interference.

equivalent number of transmit antennas $M_{\mathrm{T}_q}^{(\mathrm{eq})} = M_{\mathrm{T}}^{(\mathrm{BS})} - \sum_{g=1,g \neq q}^{Q} M_{\mathrm{R}_g}$ is equal to M_{R_q}. The reader is referred [20] for more details of the BD algorithm.

For the qth user, we propose to jointly and iteratively update the second part of its precoding matrix $\boldsymbol{G}_q$ as well as its decoding matrix $\boldsymbol{D}_q$. An equivalent channel matrix $\boldsymbol{H}_{\mathrm{e}_q}$ is defined as

$$\boldsymbol{H}_{\mathrm{e}_q} = \boldsymbol{D}_q^{\mathrm{T}} \boldsymbol{H}_q \boldsymbol{F}_q \in \mathbb{C}^{d_q \times M_{\mathrm{T}_q}^{(\mathrm{eq})}}, \tag{2.8}$$

where $\boldsymbol{D}_q \in \mathbb{R}^{M_{\mathrm{R}_q} \times d_q}$ is the real-valued decoding matrix. The proposed coordinated beamforming algorithm is summarized as follows (where p denotes the iteration index)

- **Step 1**: Initialize the decoding matrix $\boldsymbol{D}_q^{(0)} \in \mathbb{R}^{M_{\mathrm{R}_q} \times d_q}$, either randomly or using results from neighboring subcarriers.

- **Step 2**: Calculate the equivalent channel matrix $\boldsymbol{H}_{\mathrm{e}_q}^{(p)}$ based on the current decoding matrix

$$\boldsymbol{H}_{\mathrm{e}_q}^{(p)} = \boldsymbol{D}_q^{(p-1)\mathrm{T}} \boldsymbol{H}_q \boldsymbol{F}_q \in \mathbb{C}^{d_q \times M_{\mathrm{T}_q}^{(\mathrm{eq})}}. \tag{2.9}$$

  The matrix is further split into real and imaginary parts

$$\check{\boldsymbol{H}}_{\mathrm{e}_q}^{(p)} = \left[\ \mathrm{Im}\left\{ \boldsymbol{H}_{\mathrm{e}_q}^{(p)} \right\} \ \ \mathrm{Re}\left\{ \boldsymbol{H}_{\mathrm{e}_q}^{(p)} \right\} \ \right] \in \mathbb{R}^{d_q \times 2M_{\mathrm{T}_q}^{(\mathrm{eq})}}. \tag{2.10}$$

- **Step 3**: Calculate the precoding matrix $\boldsymbol{G}_q^{(p)} = \boldsymbol{G}_{q,1}^{(p)} \boldsymbol{G}_{q,2}^{(p)}$ for the pth iteration. The first part is computed from the singular value decomposition (SVD) of $\check{\boldsymbol{H}}_{\mathrm{e}_q}^{(p)}$, keeping the appropriate amount of right singular vectors to suppress the intrinsic interference. Afterwards, a new equivalent channel matrix is computed and the second part $\boldsymbol{G}_{q,2}^{(p)}$ is obtained from the SVD of this new equivalent channel in order to suppress the spatial interference.

- **Step 4**: For the precoder computed above, the decoding matrix is updated based for instance on the MMSE receiver.

- **Step 5**: Check the convergence with some measure of the changes between iterations. If the stopping criterion is not met, go back to **Step 2**.

The algorithm is described in more detail in deliverable D6.2.

2.2.2 The IIM-CBF 2 algorithm

In multi-user MIMO FBMC/OQAM downlink systems where the total number of receive antennas of the users exceeds the number of transmit antennas at the base station, the BD algorithm [20] or the BD based technique [19] cannot be employed to achieve the multi-user interference or the intrinsic interference suppression. Therefore, we propose another iterative procedure to jointly compute the precoding matrix and the decoding matrix. Let us first define an equivalent combined channel matrix after the decoding at the user terminals as

$$\boldsymbol{H}_{\mathrm{e}} = \begin{bmatrix} \boldsymbol{D}_1^{\mathrm{T}} \boldsymbol{H}_1 \\ \boldsymbol{D}_2^{\mathrm{T}} \boldsymbol{H}_2 \\ \vdots \\ \boldsymbol{D}_Q^{\mathrm{T}} \boldsymbol{H}_Q \end{bmatrix} \in \mathbb{C}^{d \times M_{\mathrm{T}}^{(\mathrm{BS})}}. \tag{2.11}$$

Unlike the coordinated beamforming schemes in [11] or [24], the decoding matrices $\boldsymbol{D}_q \in \mathbb{R}^{M_{\mathrm{R}q} \times d_q}$, $q = 1, 2, \ldots, Q$, are forced to be real-valued. Although the BD based concept cannot be employed on the physical channel due to the dimensionality constraint, it can be used on this equivalent channel. The proposed IIM-CBF 2 algorithm for the FBMC/OQAM based multi-user MIMO downlink system is very simialr to IIM-CBF 1, but at each iteration, the first additional step is to compute the precoding matrices $\boldsymbol{F}_q^{(p)}$ ($q = 1, \ldots, Q$) in order to cancel the multi-user interference, based on the BD algorithm and based on the reduced model (2.11). This has to be recomputed at each step because the decoding matrices change at each iteration.

Note that for both IIM-CBF schemes proposed in this section and Section 2.2.1, it is not required that the users are informed of the decoding matrices that are obtained at the base station while computing the precoding matrices. After the users acquire the information of the effective channel via channel estimation, the receive processing can be performed. For example, the MMSE receiver of the effective channel for each user can be employed.

2.3 Coordinated beamforming for the CoMP downlink

In this section, we focus on a CoMP downlink setting based on [11]. Note that in [11] a clustered cellular scenario is considered where each cluster contains multiple cells. Since full cooperation is assumed in each cluster, the downlink transmissions for each cluster resemble those of the single-cell multi-user MIMO downlink. Thereby, we simplify the scenario description of the CoMP downlink and only consider joint transmission of adjacent cells. It is assumed that the cell interior users only receive signals from their own base station and suffer only from the intra-cell interference, i.e., the multi-user interference as in the single-cell multi-user MIMO downlink scenarios. On the other hand, both the intra-cell interference and the inter-cell interference have an impact on the cell edge users. To assist the cell edge users to combat the interference and also deal with the greater path loss compared to the cell interior users, the base stations of the adjacent cells transmit the same signals to each cell edge user. An example of a two-cell FBMC/OQAM based CoMP downlink scenario is illustrated in Fig. 2-1.

To enable such FBMC/OQAM based CoMP downlink transmissions, the mitigation of the intra-cell, inter-cell, and intrinsic interference has to be achieved. Therefore, we propose another scheme (called IIM-CBF 3) that is an extension of the approach described in Section 2.2.2 and is also the outcome of adapting the Extended FlexCoBF algorithm for CP-OFDM based systems in [11] to FBMC/OQAM based systems. The algorithm is very similar to the one used in section 2.2.2 but incorporates the presence of inter-cell interference as well as the additional help from adjacent cells sending the same information to the cell edge users.

2.4 Summary

Finally, we summarize the proposed IIM-CBF schemes in Table 2-2. These three algorithms are all based on the concept of jointly and iteratively computing the precoding matrix and decoding matrix. In addition, they mitigate the intra-cell and inter-cell interference as well as the intrinsic interference in a ZF fashion. Nevertheless, the three schemes are designed for different configurations and deal with different types of interference. IIM-CBF 1 is developed for symmetric single-cell FBMC/OQAM based multi-user MIMO downlink settings. In this scenario, BD can still be employed to cancel the multi-user interference. Therefore, in IIM-CBF 1 only the precoding matrix for each equivalent single user transmission (i.e., $\boldsymbol{G}_q$ for the qth user) is computed via the iterative procedure to suppress the intrinsic interference. On the other
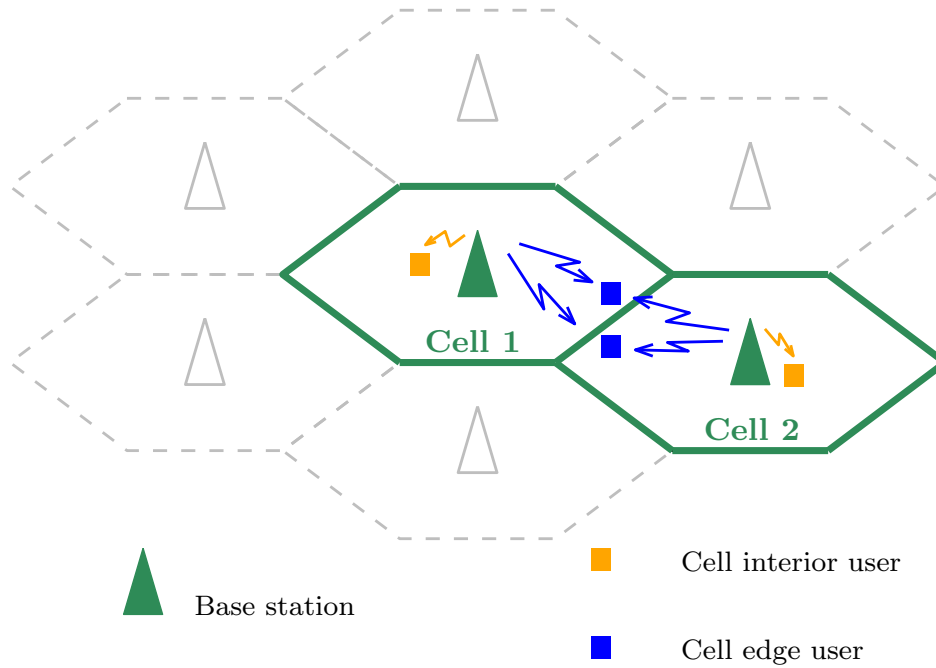
Figure 2-1: An example of a two-cell CoMP downlink scenario where a cell interior user and two cell edge users are served in each cell

Table 2-2: Acronyms of the proposed intrinsic interference mitigating coordinated beamforming (IIM-CBF) schemes and the corresponding scenarios

Acronyms	Configurations	Interference Type
IIM-CBF 1	multi-user MIMO downlink, $M_\mathrm{T}^{(\mathrm{BS})} = M_\mathrm{R}^{(\mathrm{tot})}$	intrinsic, multi-user
IIM-CBF 2	multi-user MIMO downlink, $M_\mathrm{T}^{(\mathrm{BS})} < M_\mathrm{R}^{(\mathrm{tot})}$	intrinsic, multi-user
IIM-CBF 3	CoMP downlink	intrinsic, intra/inter-cell

hand, IIM-CBF 2 is proposed to overcome the dimensionality constraint that $M_\mathrm{R}^{(\mathrm{tot})}$ must not exceed $M_\mathrm{T}^{(\mathrm{BS})}$ in the single-cell FBMC/OQAM based multi-user MIMO downlink. The complete precoding matrix (i.e., for the qth user $\boldsymbol{F}_q \boldsymbol{G}_q$) that mitigates the multi-user interference and the intrinsic interference is computed iteratively and jointly with the decoding matrix. Unlike the first two schemes, IIM-CBF 3, as a novel FBMC/OQAM based CoMP technique, is devised to enable the joint transmission of adjacent cells and to mitigate both the intra-cell interference and the inter-cell interference. In the meantime, it is able to achieve the suppression of the intrinsic interference inherent in FBMC/OQAM based systems. It is worth noting that compared to the transmission strategy reviewed in Section 2.1 as a straightforward extension of a scheme originally developed for CP-OFDM based systems, the residual intrinsic interference in case of the IIM-CBF schemes is much smaller, which will be reflected in the performance comparison in D6.2.

Simulation results will be detailed later in D6.2. They show that when the number of transmit antennas at the base station is equal to the total number of receive antennas of the users, the proposed IIM-CBF algorithm outperforms the existing transmission strategies for FBMC/OQAM based multi-user MIMO downlink systems. Moreover, it is observed that by employing the proposed IIM-CBF schemes, the FBMC/OQAM systems achieve a similar

bit error rate (BER) performance as its orthogonal frequency division multiplexing with the cyclic prefix insertion (CP-OFDM) based counterpart while exhibiting superiority in terms of a higher spectral efficiency, a greater robustness against synchronization errors, and a lower out-of-band radiation. In the presence of residual carrier frequency offsets, the superiority of the FBMC/OQAM systems over the CP-OFDM based systems is demonstrated, which corroborates the theoretical analysis that the FBMC/OQAM systems are more immune to the lack of perfect synchronization.

3. Transmission strategies for multi-user MIMO FBMC/OQAM systems in highly frequency selective channels

As reviewed in section 2, most of these state-of-the-art solutions rely on the assumption that the channel on each subcarrier can be treated as flat fading and their performance can quickly decrease for selective channels. A block diagonalization (BD) based linear precoders has been developed in [19] for the FBMC/OQAM based multi-user MIMO downlink and was reviewed in section 2.1. It adopts the central idea of BD [20] to mitigate the multi-user interference (MUI) and then uses the zero forcing based approach [16] to deal with the intrinsic interference cancellation for the resulting equivalent single-user transmissions. Furthermore, the coordinated beamforming based transmission strategies (IIM-CBF) devised in [25], [26] and described in section 2 have the advantage of alleviating the dimensionality constraint such that the number of receive antennas is not restricted. The suppression of intrinsic interference makes these methods a bit more robust to channel frequency selectivity. Nevertheless, for increasing selectivity, the violation of the assumption that the channel on each subcarrier is approximately flat also results in performance degradation.

Focusing on the case of highly frequency selective channels, the linear precoder in [27] has a structure of a filter applied on each subcarrier and its two adjacent subcarriers at twice the symbol rate. In [28], two different *quasi* minimum mean square error (MMSE) based approaches have been devised for FBMC/OQAM based multi-user multiple-input-single-output (MISO) downlink systems also considering highly frequency selective channels. A closed-form solution is provided in the first scheme, where one complex-valued fractionally spaced multi-tap precoder for each user on each subcarrier is applied at the transmitter and a single-tap real-valued weight at the receiver. The second scheme involves a joint transmitter and receiver design via an iterative procedure, where now the equalizer at the receiver side is also complex-valued fractionally spaced multi-tap. The corresponding results have been reported in the deliverable D4.3. Similar to [27], the two methods in [28] are restricted to the case where each user is equipped with a single receive antenna.

In this section, we briefly introduce the design of linear precoding and equalization schemes for the downlink of critical multi-user MISO and MIMO PMR scenarios under highly frequency selective propagation conditions, which will be detailed in deliverable D6.2.

Due to the inter-dependencies and inter-coupling between the precoder filters at the transmitter of a FBMC system, an MMSE-based precoder design is quite complex. Although we only consider ICI with the neighboring sub-carriers, in a MU-FBMC system the precoder design must additionally consider the precoder filters of all other users including the neighboring sub-carriers. To alleviate this issue, the design proposed here is based on the duality principle as introduced in [29] and [30]. The basic principle behind an MSE-duality transformation is to switch the roles of the UL and DL filters, and be able to optimize the precoding according to some MSE criterion, by applying methods used for classical MMSE receivers. To do so, we interchange each receiver filter in the UL system with the respective transmitter filter in the DL system. As the dual DL system has purely transmitter processing, we must ensure that the transmit power is subsequently limited, thus we weight every transmitter filter with a strictly real value and multiply the receiver with the inverse weighting factor.

We will investigate the different levels of duality transformations similar to those defined in [30]. These different duality transformations are summarized as follows:

- *System-Wide Sum-MSE*: equivalent to a *Level 1* transformation from [30]. This is the simplest form of duality where we keep the total sum-MSE for all users and sub-carriers

equal when transforming the UL to a DL system. We only require a single scaling factor which leads to an extremely low computational complexity.

- *User-Wise Sum-MSE*: equivalent to a *Level 2* transformation from [30]. This method preserves the sum-MSE per *user* resulting in an individual scaling factor per user for all sub-carriers and transmitter antennas. We have to solve a linear system of equations for the Q scaling factors (where Q is the number of users), thus leading to a higher computational complexity than a *Level 1* transformation.

- *Sub-Carrier-Wise Sum-MSE*: equivalent to a *Level 2* transformation from [30]. This method preserves the sum-MSE per *sub-carrier* resulting in an distinct scaling factor per sub-carrier for all users and transmitter antennas. Again, we have to solve a linear system of equations for the M scaling factors, which leads to a higher computational complexity that a *User-Wise Sum-MSE* and *Level 1* transformation.

- *User and Sub-Carrier-Wise MSE*: equivalent to a *Level 3* transformation from [30]. This method preserves the individual MSE for every single *user* and *sub-carrier*. This results in a scaling factor per user and per sub-carrier for all transmitter antennas. Evidently, a *Level 3* duality transformation requires the highest computational complexity because we have to solve for MQ different scaling factors. However, this method guarantees that the individual MSEs per user, per sub-carrier will stay equal for the UL SIMO and DL MISO systems.

The two design methods investigated in D6.2, are introduced below.

3.1   Iterative design of MMSE based precoder and real-valued receive spatial filter

Stemming from the problem formulation in [28], we first develop an iterative approach, where MMSE based multi-tap precoders are designed to effectively mitigate the MUI, inter-symbol interference (ISI), and inter-carrier interference (ICI). At each user terminal equipped with multiple antennas, only a receive spatial filter is applied. Via an iterative design, the precoders and the receive spatial filters are jointly optimized. In this iterative design, the precoders and the spatial filters are updated alternately. First given the spatial filter, the precoder are designed on a per sub-carrier basis to compensate for ISI, ICI and MUI. More specifically they minimize the mean square error via the duality principle, with a method similar to the one presented in [28]. After computing the precoders, the spatial filters are updated based on the maximal-ratio combining (MRC) criterion, assuming that the MUI, ISI, and ICI have been canceled completely.

The real-valued coefficients of the receive spatial filter can be initialized randomly. A stopping criterion is used based on monitoring the changes at each iteration.

3.2   Signal-to-leakage (SLR) based precoder and real-valued receive spatial filter

Similar to the iterative design, we again consider a real-valued spatial filter at each user node. Instead of jointly and iteratively updating the precoder and the spatial filter, we propose a closed-form SLR based linear precoder. The mathematical details will be provided in D6.2. The

optimization is based on a criterion that takes into account the intersymbol interference (ISI) as well as the interference that is leaked to other users, and adjacent subcarriers (MUI and ICI). When the precoder is computed, an MRC based spatial filter is employed at each user node. Once again, it relies on the assumption that the MUI, ISI and ICI have been mitigated by the SLR based precoders at the base station. Note that the extension of this SLR based scheme to the case of multiple spatial streams per user can be conveniently conducted based on a similar philosophy introduced in [31].

The numerical results, presented in D6.2, show that the proposed schemes achieve a very promising performance in case of highly frequency selective channels. They significantly outperform the state-of-the-art approaches that suffer from impractical restrictions on the channel frequency selectivity. The dual precoders all outperform the original precoder-[28] design in terms of BER and MSE over a wide SNR range. Furthermore, the MSE values of the dual precoder designs all outperform the precoder-[28] design and saturate where the precoder-[28] design does not since it does not take the noise into account during the calculations. From the numerical results it can be concluded that the first approach provides a slightly better performance compared to the second method, at the cost of a higher complexity due to the joint transceiver design. Moreover, both approaches show a considerable improvement over two state-of-the-art schemes that do not consider the channel frequency selectivity inside each subcarrier.

4. Preamble-based MIMO channel estimation in FBMC based distributed MIMO systems

All precoding and beamforming methods presented in previous sections rely on CSI. So it is necessary to investigate how this channel information can be obtained, in particular in the distributed case where full coordination and full synchronization between the base stations is not always available.

We consider the downlink of a distributed MIMO system having K_t base stations (transmitters) and U users (receivers). Figure 4-1 depicts an example of the considered system with $K_t = 3$ base stations and $U = 2$ users. We assume that each node is equipped with a single transmit/receive antenna. Two multicarrier techniques are considered: the Cyclic Prefix based Orthogonal Frequency Division multiplexing (CP-OFDM) and the Offset-QAM based Filter Bank MultiCarrier scheme (FBMC-OQAM). We assume that the channel is mildly frequency selective and that the number of subcarriers M is sufficiently big so that each subcarrier experiences a flat fading channel. Accordingly the inter-carrier interference (ICI) becomes negligible. We also assume that the propagation channels are stationary during the downlink frame period. This is the case for time-invariant or slowly varying channels. Our aim in this work is to estimate the distributed MIMO channel.

A *preamble-based* channel estimation is considered. The important consequence is that, during the channel estimation procedure, CSI is not known yet and synchronization may not be known either. Hence we have to work under the assumption that the precoding is not yet possible during the preamble duration and that the preamble streams to the different users can suffer from (multi-stream) interference. Similarly, it is also important to investigate the effect of imperfect synchronization among the various base stations. In order to overcome the issue of this multi-stream interference, we propose to use two different subcarriers assignment schemes (SAS) during the preamble phase. The reason behind the use of specific SAS is to ensure the orthogonality between the K_t transmitted preamble streams. It is worth mentioning that each transmitted signal occupies the entire frequency bandwidth during the rest of the frame period, i.e. during data transmission once the precoding has been computed.

Assuming that the number of subcarriers M is bigger than the number of transmitted streams K_t with $\lfloor \frac{M}{K_t} \rfloor = m$, each receiver obtains at best m measurements of each channel frequency response (CFR). In order to ensure the recovery of the transmitted information and the computation of the precoding on all subcarriers, it is obvious that we need the knowledge of all M points of each CFR. These M points can be computed from the m measurements thanks to the time domain channel response sparsity. In fact, experimental results demonstrate that multipath channels exhibit a sparse structure [32] meaning that most of the channel energy is concentrated in a few delay values. Consequently, exploiting the sparsity of each channel impulse response(CIR), we are able to reconstruct the required M frequency response points provided that the number of measurements m is bigger than the number of non-zero impulse response coefficients. In this section, we focus on two subcarriers assignment schemes (SAS) depicted in Figure 4-2, namely, the block SAS and the equispaced SAS:

- Equispaced SAS: In this scheme, the assigned subcarriers to each user are allocated uniformly over the whole bandwidth. To sustain inter-user orthogonality, δ free subcarriers serve as guard bands between the different pilot subcarriers. The advantage of this scheme is that the pilot subcarriers are well distributed over the whole bandwidth inducing very little correlation between each other. However, one can note that this scheme results in a large number of subcarriers used as guard bands to sustain inter-user orthogonality:
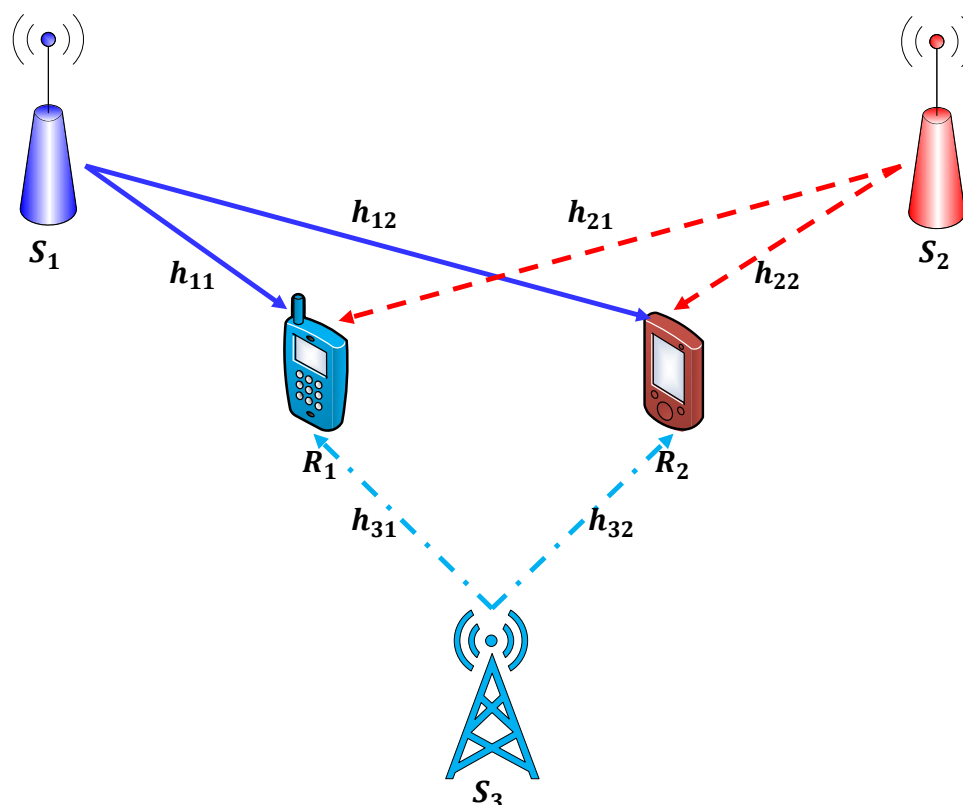
Figure 4-1: OFDM/FBMC distributed MIMO system: $K_t = 3$ Transmitters and $U = 2$ Receivers

maximum $\lfloor \frac{M}{(\delta+1)K_t} \rfloor$ subcarrier pilots can be assigned to each source. The next assignment scheme mitigates this issue by using blocks of subcarriers.

- Block SAS: In this scheme, several blocks of consecutive adjacent subcarriers in the preamble are allocated to each transmitter. δ free subcarriers adjacent to each block serve as guard bands between the different blocks. The ratio of pilot subcarriers versus guard band subcarriers is much more favorable in this case compared to the latter. However, this scheme may lead to performance degradation given that the subcarriers are more correlated and give a worse overview of the whole bandwidth.

Depending on the synchronization between the transmitters, we analyze two scenarios:

- Perfectly synchronized scenario: In CP-OFDM, there is no need of guard bands since the orthogonality between subcarriers is ensured in the complex domain. On the other hand, since the orthogonality in FBMC-OQAM is restricted to the real domain, guard bands of one or two subcarriers are needed between different blocks to ensure the orthogonality. In fact, the orthogonality is no longer guaranteed between subcarriers belonging to different users due to the phase difference between the corresponding subchannel gains. It is worth pointing out that the guard band size mainly depends on the utilized prototype filter.

- Unsynchronized scenario: The timing asynchronism between the different transmitted signals may cause a loss of orthogonality between the blocks leading to inter-user interference. In order to avoid this interference, we have to insert guard bands of several subcarriers in the CP-OFDM case while no additional subcarriers are needed in the FBMC
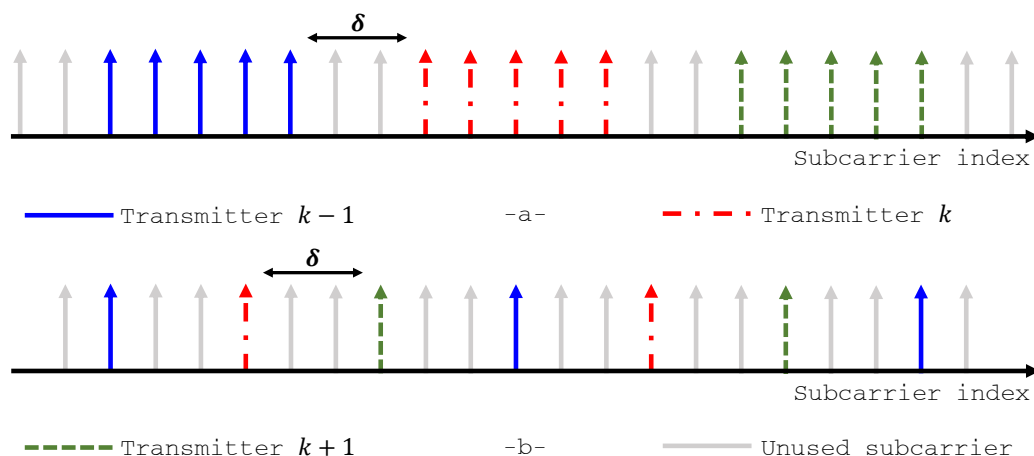
Figure 4-2: subcarriers assignment schemes: -a- block, -b- equispaced, guard band size $\delta = 2$ subcarriers

case except those already inserted in the perfectly synchronized case thanks to its well localized prototype filter.

In [33], the authors show that for both CP-OFDM and FBMC-OQAM systems, all equis-paced preambles with a number of pilots L_p larger or equal to the channel length L_h minimize the MSE of the CFR estimates, subject to a constraint on the total transmitted energy. In-deed, block SAS leads to noise amplification degrading the final CFR MSE. However, it should be noted that the optimization of [33] is conducted in the SISO case only. It does not in-vestigate the synchronization issues that can occur in the present distributed MIMO scenario. Furthermore, it assumes there is always enough pilots to be able to recover the entire CIR $L_p = \lfloor \frac{M}{(\delta+1)K_t} \rfloor \geq L_h$, which is not always true in our MIMO case, especially for a large number of users.

The study presented in D6.2 analyzes the behavior of different SAS both in CP-OFDM and FBMC-OQAM and in both synchronized and unsynchronized cases. It is shown that in unsynchronized cases, only the equispaced SAS with maximum spacing $L_p = L_h$ is optimal when there is no lack of pilots. It allows to have a maximal guard band size δ to protect the different pilots from inter-user interference. Furthermore it is shown that in some cases of lack of pilots, the block SAS outperfoms the equispaced SAS in FBMC-OQAM.

To reconstruct the entire CFR based on the pilot estimates, two methods are considered:

- A minimum mean squared error estimator, which is optimal in terms of MSE, but requires the knowledge of the channel covariance matrix and noise covariance matrix. At high SNR, it reduces to applying the pseudo inverse of the DFT sub-matrix corresponding to the used pilots. It can also be shown that, under common hypotheses, this estimator will converge towards the true CFR at very high SNR.

- An iterative technique described in [34] and [35] which is based on alternating between the frequency and time domain, using the information from the pilots at some specific frequencies and applying the constraint on the time duration of the channel. The big advantage of this algorithm is that it is computationally efficient (it was standardized in HIPERLAN/2 for this reason). Furthermore, it does not require the channel and the noise covariance matrices.

The relation between both methods is also investigated. It is shown that the steady state of the iterative technique is the pseudo-inverse of the DFT sub-matrix corresponding to the used pilots which is nothing else than the MMSE estimator at high SNR. Note that, in the case of FBMC/OQAM, both considered methods assume a reasonably flat channel. For high frequency selectivity, interference occurs which is not taken into account in the model and which causes a performance floor.

5. References

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