A Survey on the Successive Interference Cancellation Performance for Single-Antenna and Multiple-Antenna OFDM Systems

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***Abstract*—Interference plays a crucial role for performance degradation in communication networks nowadays. An appealing approach to interference avoidance is the Interference Cancellation (IC) methodology. Particularly, the Successive IC (SIC) method represents the most effective IC-based reception technique in terms of Bit-Error-Rate (BER) performance and, thus, yielding to the overall system robustness. Moreover, SIC in conjunction with Orthogonal Frequency Division Multiplexing (OFDM), in the context of SIC-OFDM, is shown to approach the Shannon capacity when single-antenna infrastructures are applied while this capacity limit can be further extended with the aid of multiple antennas. Recently, SIC-based reception has studied for Orthogonal Frequency and Code Division Multiplexing or (spread-OFDM systems), namely OFCDM. Such systems provide extremely high error resilience and robustness, especially in multi-user environments.**

In this paper, we present a comprehensive survey on the performance of SIC for single- and multiple-antenna OFDM and spread OFDM (OFCDM) systems. Thereby, we focus on all the possible OFDM formats that have been developed so far. We study the performance of SIC by examining closely two major aspects, namely the BER performance and the computational complexity of the reception process, thus striving for the provision and optimization of SIC. Our main objective is to point out the state-of-the-art on research activity for SIC-OF(C)DM systems, applied on a variety of well-known network implementations, such as cellular, *ad hoc* and infrastructure-based platforms. Furthermore, we introduce a Performance-Complexity Tradeoff (PCT) in order to indicate the contribution of the approaches studied in this paper. Finally, we provide analytical performance comparison tables regarding to the surveyed techniques with respect to the PCT level.

***Index Terms*—Orthogonal Frequency Division Multiplexing (OFDM), Successive Interference Cancellation (SIC), Multiple-Input Multiple-Output (MIMO), Iterative Reception, Successive Decoding.**

I. Introduction

In MODERN wireless communication networks, Orthogonal Frequency Division Multiplexing (OFDM) has been proposed as one of the key technologies for modulation and signal propagation. Recently, most of the research concern has focused on its multi-user access method, Orthogonal Frequency Division Multiple-Access (OFDMA), as it provides acceptable performance on numerous applications [1]. IEEE 802.20 Mobile Broadband Wireless Access (MBWA) [2], [3], Worldwide interoperability for Microwave Access (WiMAX) [4], 3GPP Long-Term Evolution (LTE) [5] and next-generation Wireless Wide Area Network (WWAN) [6] are some of the most representative OFDM-enabled network standards. The main reasons for the OFDM popularity are (a) the achievement of a high data rate performance due to the provision of spectral efficiency in comparison to prior modulation schemes, such as Code Division Multiple Access (CDMA) and (b) the efficient adaptation to the frequency selectivity of the channel, due to the orthogonality principle.

Nevertheless, the growing need for Quality-of-Service (QoS) enhancements along with the dense multi-user tenet in recent OFDM(A) infrastructures contradict mainly to capacity limitations and thereby encloses potential user demands or application perspectives. Interference plays a crucial role in the above mentioned limitations, while induces a typical upper bound to the system performance. More than any other single effect, interference can lead to quite catastrophic results at a typical OFDM receiver [7], [8]. Since the outage probability is predominantly caused by the interference appearance, an appealing alternative to interference avoidance is Interference Cancellation (IC).

IC is divided into two main categories, namely pre-IC and post-IC. Pre-IC represents a family of techniques established at the transmitter side, which are focused on the cancellation or the suppression of interference on a *priori* basis. An essential precondition for pre-IC to cancel the interference effect is the establishment of the appropriate precoding technique. Some representative precoding examples applied on OFDM systems are the Selected Mapping (SLM), the Partial Transmit Sequences (PTS) and the Dirty Paper Coding (DPC) [9], [10]. Especially DPC represents quite an effective pre-IC precoding method [11], which is implemented at the transmitter by taking into consideration the interference amount (experienced at the receiver) before the signal transmission. Thereupon, a suppressed from the ongoing interference signal is transmitted accordingly. In order for the transmitter to efficiently pre-estimate the level of the ongoing interference, reliable Channel State Information (CSI) via signaling is more than a prerequisite. Hence, feedback and/or feed-forward signaling overhead is necessary in order to preserve critical up-to-date interference information at the transmitter side, constantly. As CSI is more

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accurate and reliable, the pre-IC techniques become more error resilient. However, perfect CSI is very difficult to accomplish in real conditions and, therefore, a potential error at the pre-IC process may occur with high probability. The imperfect CSI gets more emphatic as user mobility is introduced or the number of potential system users is increased, i.e. within a multi-user environment. Furthermore, keeping a detailed interference profiling for all the transmitting users induces the error probability on the precoding process while enormously increases the signaling overhead, yielding to an overall system inefficiency.

On the other hand, post-IC represents a family of techniques established at the receiver side, which are focused on the interference cancellation on *a posteriori* basis. In general, it should be expounded as *the class of techniques that decode desired information and then use this information along with channel estimates to cancel a fraction of the received interference from the overall received signal* [7], [12], [13]. Therefore, signal processing is required after signal detection in order to classify the system as post-IC. Unlike pre-IC, in a post-IC framework the signaling overhead between the transmitter and the receiver side is not necessary. The entire processing takes place at the receiver side and the presence of CSI is only optional (e.g. blind IC-based reception). Due to these reasons, post-IC represents quite an adaptable IC methodology, appropriate for numerous OFDM implementations.

Post-IC methodology can generally be broken into two major categories, namely parallel and successive, although recent developments in an iterative post-IC regime have blurred the distinction. Parallel Interference Cancellation (PIC) fundamentally operates by detecting all the users simultaneously. This quite coarse estimation can be used to cancel some interference whereas the parallel detection can be repeated in a number of stages to improve both the system reliability and robustness with respect to the error resilience and the Bit-Error-Rate (BER) probability [14]. However, this approach causes a rather inefficient reception performance as it is susceptible to errors and the probability for inaccurate detection is quite high. Furthermore, PIC requires precious hardware gear in order to operate in parallel, which makes it unprofitable for numerous practical implementations [7], [15].

A particularly interesting type of IC reception which overcomes the above mentioned restrictions is Successive Interference Cancellation (SIC), first suggested in [16]. The key idea of SIC is that users are decoded successively. After one user is decoded, its signal is stripped away from the aggregate received signal *before* the next user is decoded. When SIC is applied, one of the users, say $user_1$, is decoded treating $user_2$ as interference, but $user_2$ is decoded with the benefit of the signal of $user_1$ already removed. In contrast, using conventional reception, every user is decoded treating the other interfering users as noise. It is then straightforward that the later scheme is suboptimal in comparison to SIC in terms of reliability, system robustness and, hence, capacity with respect to the aggregated throughput at the receiver [17]. In order to further enhance the performance and the accuracy of SIC, an optimal decision ordering can be potentially applied on the signal detection process which will correspondingly result to the decoding of the strongest user first, i.e. the user which experiences the best Signal-to-Interference-plus-Noise-Ratio (SINR) and/or Signal-to-Noise-Ratio (SNR). In general, users should be decoded in the order of their received powers (even though this is not always the most preferable choice from an information theoretic perspective [18]). From the above mentioned discussion, we state that SIC aims to efficiently turn the *interference problem* into an *interference advantage* in order to achieve capacity and performance gain, as compared to the conventional non-SIC reception.

In this paper, an illustrative analysis of SIC-enabled reception is thoroughly provided for the prominent wireless OFDM communication networks, namely the SIC-OFDM systems, as they represent a major topic for research and development currently. The study concerns the conventional single-antenna and the propitious multiple-antenna OFDM transceiver modes for SIC reception. In addition, both the unspread and the more robust Orthogonal Frequency and Code Division Multiplexing (OFCDM or spread OFDM) design versions are considered in order to provide a rather exhaustive analysis of the field, resulting to a compact study of the SIC performance at all the available OFDM formats so far.

Most of the research community, which has focused on the SIC-OFDM amelioration, tends to optimize two factors. These are (a) the BER performance and (b) the overall computational complexity reduction, which both represent cornerstone requirements for the SIC efficiency. Unfortunately, the enhancement of the former factor contradicts the later and vice versa. In fact, as the SIC becomes more robust and accurate in terms of BER performance, the overall complexity of the iterative detection and decoding process increases dramatically. We, therefore, introduce the term Performance-Complexity Trade-off, namely *PCT*, to point out the above mentioned fragility. All the surveyed contributions into this paper have classified with respect to PCT. In this paper, we refer to the system performance, accuracy, reliability and robustness with respect to the BER performance and error resilience. Furthermore, we refer to the system capacity with respect to the overall system throughput and/or the maximization of the number of system users.

II. Preliminaries

In OFDM systems, the interference effect is generated mainly due to the channel radio conditions and/or the user transmissions occurring on adjacent subcarriers, regarding either single or multiple access environments. A sophisticated design of the OFDM transceiver plays, therefore, a crucial role to the interference suppression and, thus, to the communication establishment successfully, e.g. the appropriate adoption of encoding, interleaving or spreading methods. In this section we briefly describe fundamental OF(C)DM concepts of the transmitter and the receiver side (from the interference cancellation viewpoint) as well as basic channel influences responsible for signal degradation scenarios, since they represent significant impacts on the SIC performance.

A. Notation

The notations used throughout this paper are the following ones. Vectors and matrices are represented by lowercase bold

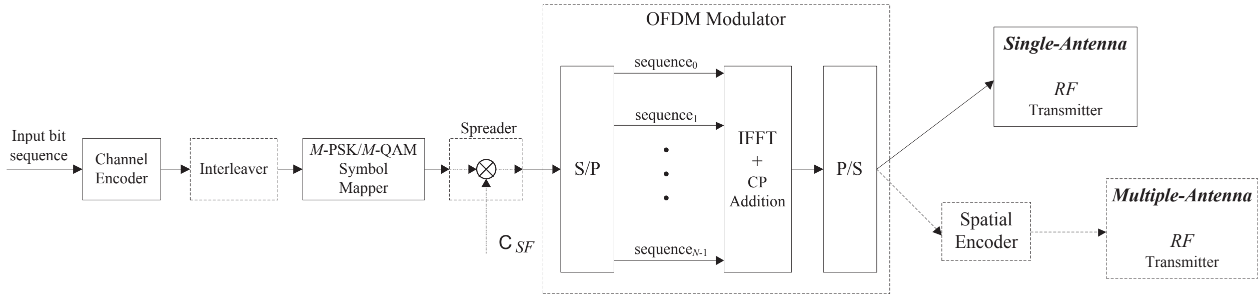

Fig. 1. Block diagram of a typical OFDM transmitter. The Interleaver and Spreader components indicated by dashed lines are present only for BICM and OFCDM transmissions, respectively. Likewise, the Spatial Encoder and the Multiple-Antenna *RF* Transmitter components are utilized only in multiple-antenna infrastructures, which are thoroughly discussed in Section V.

typeface and uppercase bold typeface letters, respectively. $\mathbf{A}_{a,b}$ denotes the (a, b)th element of $\mathbf{A}$. $E\{.\}$ stands for the statistical mean. A complex Gaussian random variable with mean m and variance σ^2 is denoted by $\mathcal{G}$ (m, σ^2). Superscripts $(.)^T$ and $(.)^H$ denote the transposition and the conjugate (or Hermitian) transposition, respectively.

B. OFDM Transmitter

Figure 1 depicts the structure of the transmitter block for a typical OFDM system. First, the information input bits are appropriately encoded through a channel encoder. Afterwards, they are bit-by-bit interleaved and then converted to QAM symbols according to a Gray-coded constellation Bit-Mapper (BMAP). This scheme is also known as Bit-Interleaved Coded Modulation (BICM) [19] and provides further robustness compared to the conventional transmission schemes in terms of BER performance, due to the successful combination of coding and interleaving before the bit mapping procedure. In fact, BICM optimizes the system accuracy and robustness since severe channel selectivity-dominant to current and future network designs-determines the propagation attenuation behavior of the OFDM signals. Especially when both time and frequency (i.e. double) selectivity is present, both coding and interleaving represent an essential parameter that allows for efficiency enhancement in OFDM systems. Nevertheless, it represents only an optional selection which aims to optimize the OFDM transceiver block in terms of BER performance and system robustness.

When OFCDM is used instead of the unspread conventional transmission, the subsequent procedure takes place before the OFDM modulation. The encoded symbols are being spread symbol-by-symbol by a particular code $C_{\mathcal{SF}}$. The objective of the OFCDM transmission-reception mode is to enhance the system accuracy and to efficiently exploit multi-user diversity, with respect to the conventional (unspread) OFDM approach, especially in dense multiple access environments. In order to improve the quality of the signal and, therefore, to reduce the interference level at the receiver, the mutual information must be kept at a minimum level. Hence, the $C_{\mathcal{SF}}$ codes have chosen to be orthogonal (e.g. Walsh- Hadamard codes) or quasi-orthogonal (e.g. *PN*-sequences), while a unique signature codeword is assigned to each user. In general, orthogonality is one of the most important principles in OFCDM, borrowed by the conventional CDMA, which isolates user signals according to their signature codewords at the receiver and preserving all the extrinsic information at the appropriate noise level. Then, the output signal is serial-to-parallel converted for OFDM modulation according to the N available subcarriers, as shown in figure 1. For notational simplicity, at the OFCDM transmitter case we assume that the number of OFDM subcarriers is equal to the spreading code length (i.e. $N = C_{\mathcal{SF}}$), where each information sequence transmitted from a specific user comprises an individual OFDM symbol. Otherwise, (if $N > C_{\mathcal{SF}}$), each OFDM symbol may consist of several parts of different users' information bits.

OFDM modulation is accomplished using the N-point Inverse Fast Fourier Transform (IFFT). In order to avoid the Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) effects, dominant in OFDM systems, a guard interval, e.g. a Cyclic Prefix (CP), is appropriately added to each IFFT sequence before the OFDM block transmission. Then, all the sequences are parallel-to-serial converted to form an OFDM block (or stream). Finally, in case of single-antenna infrastructures, the output OFDM block is transmitted to the wireless channel via an *RF* transmitter. In case of multiple-antenna infrastructures, the output OFDM block passes through the appropriate spatial encoder and then to a multiple-antenna *RF* transmitter (both components are thoroughly discussed in section V), as shown in figure 1.

C. Basic OFDM Channel Conditions

The frequency selectivity of the wireless channel is a crucial parameter for QoS degradation in modern OFDM systems. Especially when such systems support high mobility, double selectivity is present. In addition, the provision of the performance in these schemes is further challenged in urban terrestrials where the existence of Rayleigh fading, due to the rich scattering environments, and the lack of Line-Of-Sight (LOS) signal transmissions, determines the amount of signal decay at the receiver. In particular, the most crucial performance degradation influences in the OFDM transmissions are listed below:

- the propagation attenuation (mostly due to the distance between the transmitter and the receiver)
- the ISI effect (due to the multipath propagation)

- the ICI effect (mainly due to the loss of the tight frequency synchronization between the transmitter and receiver, which results in the loss of subcarrier orthogonality)
- the existence of the unavoidable Additive White Gaussian Noise (AWGN)

Figure 2 shows the major impacts experienced by a typical OFDM receiver, from the interference viewpoint, whereas the included numerous interference influences are discussed in detail subsequently, as it is the main subject of this paper. Assuming that ISI and multipath fading can be eliminated by choosing a suitable size for the CP prefix, a sophisticated decision for the length of this size is a rather determinant criterion for QoS provision in OFDM systems. In general, ICI represents the main performance degradation influence in a typical OFDM receiver. Two essential reasons for its realization are the self-interference and the so-called Multiple Access Interference (MAI). The former is due to the power leakage to/from adjacent subcarriers of the same user and the later is due to the power leakage to/from adjacent subcarriers caused by other users' transmissions, when multiuser environments are considered. Despite the interference suppression by the CP, the ICI effect and the AWGN aggregation to the received information still remain the main challenges for an OFDM receiver to be dismantled.

Moreover, from the frequency synchronization perspective, a typical OFDM channel is assumed to be synchronous for the forward link transmissions while is usually assumed to be asynchronous or quasi-synchronous for the reverse link transmissions (i.e. all uplink transmissions are assumed to be synchronous since they are bounded within the CP margin). The later distinction plays an important role on infrastructure-based and capacity-limited OFDM systems, such as the cellular networks, in terms of efficient reception, as it is further discussed in the next section.

D. OFDM Receiver

For each OFDM block the input-output relationship can be described, after the CP extraction, as [20]-[22]

$$\mathbf{y} = \mathbf{F}\mathbf{G}_t\mathbf{F}^H\mathbf{x} + \mathbf{F}\mathbf{w}_t = \mathbf{F}\mathbf{G}_t\mathbf{x}_t + \mathbf{F}\mathbf{w}_t = \mathbf{G}\mathbf{x} + \mathbf{w}, \quad (1)$$

where $\mathbf{y} = [y_1, y_2, ..., y_N]^T$, $\mathbf{x} = [x_1, x_2, ..., x_N]^T$ and $\mathbf{w} = [w_1, w_2, ..., w_N]^T$ are the $N \times 1$ received signal vector, the transmitted signal vector and the AWGN received vector in the frequency domain, respectively. Likewise, $\mathbf{x}_t$ and $\mathbf{w}_t$ represent the $N \times 1$ received signal vector and AWGN received vector in the time-domain, respectively. $\mathbf{G}_t$ is the $N \times N$ channel matrix in the time-domain. $\mathbf{F} = (1/\sqrt{N})[exp(-j2\pi(a-1)(b-1)/N)]_{a,b=1,2,...,N}$ and $\mathbf{G}$ denote the $N \times N$ Fast Fourier Transform (FFT) matrix and $N \times N$ channel matrix in the frequency-domain, respectively.

In ideal channel conditions, $\mathbf{G}$ is typically a diagonal matrix. However, severe channel selectivity, present in numerous modern network applications, makes the ICI effect feasible mostly on adjacent OFDM subcarriers. Since the off-diagonal channel matrix elements cause the occurrence of ICI, $\mathbf{G}$ is typically a non-diagonal matrix and that is the main reason for performance degradation in general. Hence, taking into account the ICI contribution and focusing on the decoding of the *i*-th user, the received signal can further decomposed to the following expression as

$$\mathbf{y} = \widetilde{\mathbf{G}}\mathbf{x} + \underbrace{\sum_{j=0}^{N^i-1}\sum_{k=0}^{N-1} I^i_{j,k}}_{self-interference} + \underbrace{\sum_{\substack{p=0,\\ p\neq i}}^{U-1}\sum_{j=0}^{N^p-1}\sum_{k=0}^{N-1} I^p_{j,k}}_{MAI} + \mathbf{w}, \quad (2)$$

where $\widetilde{\mathbf{G}}$ denotes the interference-free channel matrix, U denotes the total number of users, N^i denotes the number of subcarriers assigned to the *i*-th user, and $I^i_{j,k}$ denotes the ICI contribution of the *j*-th subcarrier of the *i*-th user on the *k*-th subcarrier, under multiuser network scenarios. In case of single-user scenarios, all the OFDM subcarriers are assigned to the *i*-th user (i.e. $N^i = N$, $U = 1$) and MAI is removed. Usually, the above mentioned interference contributions are modeled as Gaussian processes since they are considered as random events. Moreover, the modeling of such interference events is crucial for the overall reception performance and thus represents one of the main aspects considered into this paper, which is further discussed and analyzed in the next sections.

Upon the received mutual information and before the signal detection and decoding, OFDM demodulation is accomplished via the N-point $\mathbf{F}$ matrix, as figure 3 shows. Thereupon, only in case of OFCDM, an appropriate despreading is necessary in order to recompose the initial information, transmitted by each user.

Then, SIC is responsible for the appropriate detection and decoding of the output data by decomposing the overall signal in the useful information (each user's data) and the extrinsic information. SIC can be directly applied on both Single-User Detectors (SUD) and Multi-User Detectors (MUD) for OFDM applications. Recently, MUD has dominated over the prior SUD reception type, by simultaneously receiving multiple interfering users, mostly due to the achievement of performance and capacity gain [23]. The received signal is then regenerated taking into account both CSI and the extrinsic information while the most dominant interferer is being canceled according to specific detection ordering criteria and sent back to the detector for sampling evaluation and so on, until all interfering users have been canceled. The number of iterations is not determined only by the number of the interfering users but most importantly by the considered number of SIC stages, which are mainly predetermined by the system engineer or the network manufacturer.

The equalization strategy, i.e. the front-end of a receiver, may have any type of structure. However, the selection of the appropriate equalizer for OFDM systems plays a crucial role to SIC performance as it is further discussed in the next sections. Typically, the most common equalization techniques used for detection and decoding at OFDM receivers are the optimal Maximum Likelihood (ML) criterion and the suboptimal linear Minimum Mean Squared Error (MMSE) and Zero Forcing (ZF) strategies. ML achieves the best performance since it is the most error resilient equalizer at the expense of the highest computational complexity. It represents quite an exhaustive detection method by searching between the overall received signal and the most appropriate symbol estimation for all

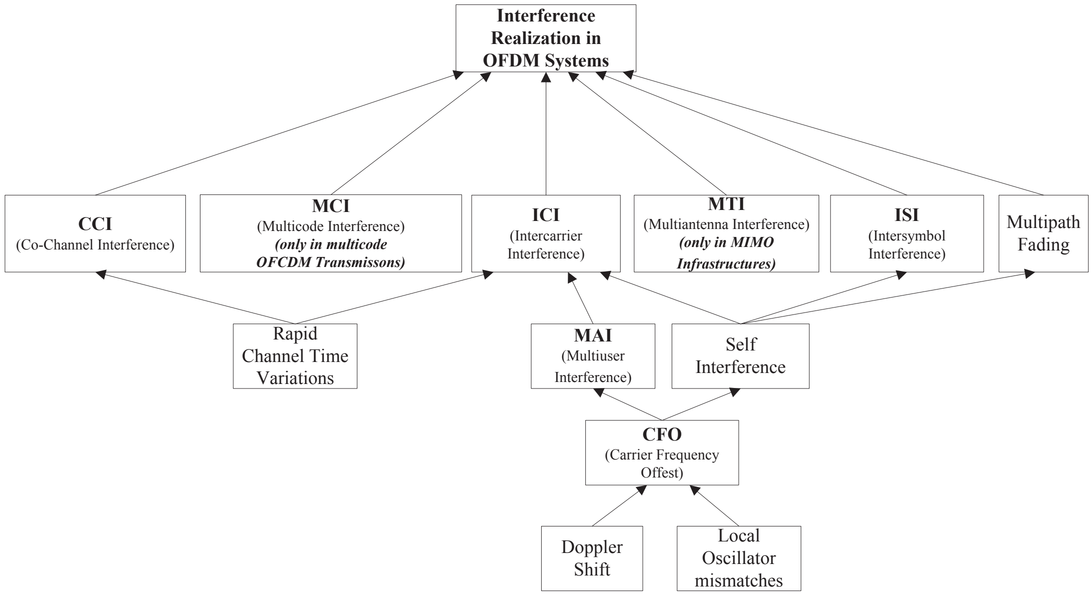

Fig. 2. Representation of the major interference influences in OFDM systems.

the possible combinations on a given constellation alphabet. ZF, on the other hand, has the slightest complexity but it is susceptible to errors. It is performed by estimating the Moore-Penrose pseudoinverse of a given channel matrix. MMSE balances appropriately the benefits and the drawbacks of the two above mentioned techniques, regarding the PCT level. It calculates an appropriate matrix inversion by taking into consideration both the channel status and the noise variance. These methods are further discussed and analyzed in the following sections by illustrating several case studies.

Particularly, there are two different types of SIC strategies, namely the hard- and soft-SIC, as shown in figure 3. These terms refer to the decision policy or strategy which is used in the equalization and the detection process. Using a *hard* decision policy, the detection and, thus, the decoding process is implemented by conventional reception strategies, e.g. hard Viterbi decoding. A *soft* decision policy is a more sophisticated reception strategy which aims to optimize the BER performance. In this case, the received signal is demodulated by an iterative Soft-Input-Soft-Output (SISO) inverse bit mapper. Particularly, in BICM schemes, the received QAM symbols are first demodulated by a soft-output demapper and de-interleaved, and then passed to a standard binary soft-input Viterbi decoder [24]. The main difference between a soft and a hard Viterbi decoder is that the soft values have the same sign as the later decoder whereas their absolute values indicate the reliability of the decision [25]. A Maximum *a Posteriori* (MAP) estimator is usually adopted based on a Log-Likelihood Ratio (LLR) value approximation, in order to accomplish soft detection. Even though the hard decision is less complex and less time consuming, it provides significant performance degradation compared to the soft decision policy. It is, therefore, clear that the appropriate selection for SIC, i.e. to be either hard- or soft-enabled, debates for the PCT optimality and depends mostly on the application requirements. As the appropriate decision policy for equalization or data decoding does not represent the primary subject of this paper, no further analysis is given for hard or soft equalization methodologies. A detailed analysis on the performance of hard and soft decision approximation for M-ary constellations, used constantly in OFDM systems, may be found in [25]-[27].

Finally, the reconstructed hard or soft output passes through a channel re-estimator, where the received signal is regenerated including all the extrinsic information but without the interference contribution of the last decoded and already canceled symbol. Thereupon, at the next SIC stages the remaining users signals go through a more advantageous decoding process in terms of accuracy and BER performance since the interference level at the receiver is somehow relaxed. Afterwards, the same procedure follows on for the next interfering user and so on, until the extrinsic information from all the available interferers has been canceled out.

Overall, we highlight the most important steps of the SIC-based reception more specifically as

1) Upon a signal reception, calculate the equalization $N \times N$ matrix $\mathbf{J}$, where $\mathbf{J}$ could be either an ML, a ZF or an MMSE detector ($\mathbf{J}$ is represented by various forms depending on the detection policy, as analytically described in the next section)
2) Apply an optional detection ordering $\mathcal{B}_l$ on $\mathbf{J}$, $l \in (0, N]$
3) Calculate $\langle \mathbf{J}\ \mathbf{y} \rangle_l$, where $\langle . \rangle_l$ denotes the l-th row of a matrix. The resulting term denotes an estimation of the detected symbol x, which can subsequently be decoded according to the modulation type which is used.
4) Subtract the decoded information from the remaining signal as $\mathbf{y}_{new} = \mathbf{y}_{previous} - x\,[\mathbf{G}]_l$, where $[.]_l$ denotes the l-th column of a matrix
5) Relax the channel matrix in terms of interference contribution as $\mathbf{G}_{new} = [\mathbf{G}]_{l'}$, where l' is the deflated version of a matrix whose $1, 2, ..., l$-th columns have been zeroed
6) Repeat steps 1 to 5 until all the OFDM symbols have been decoded

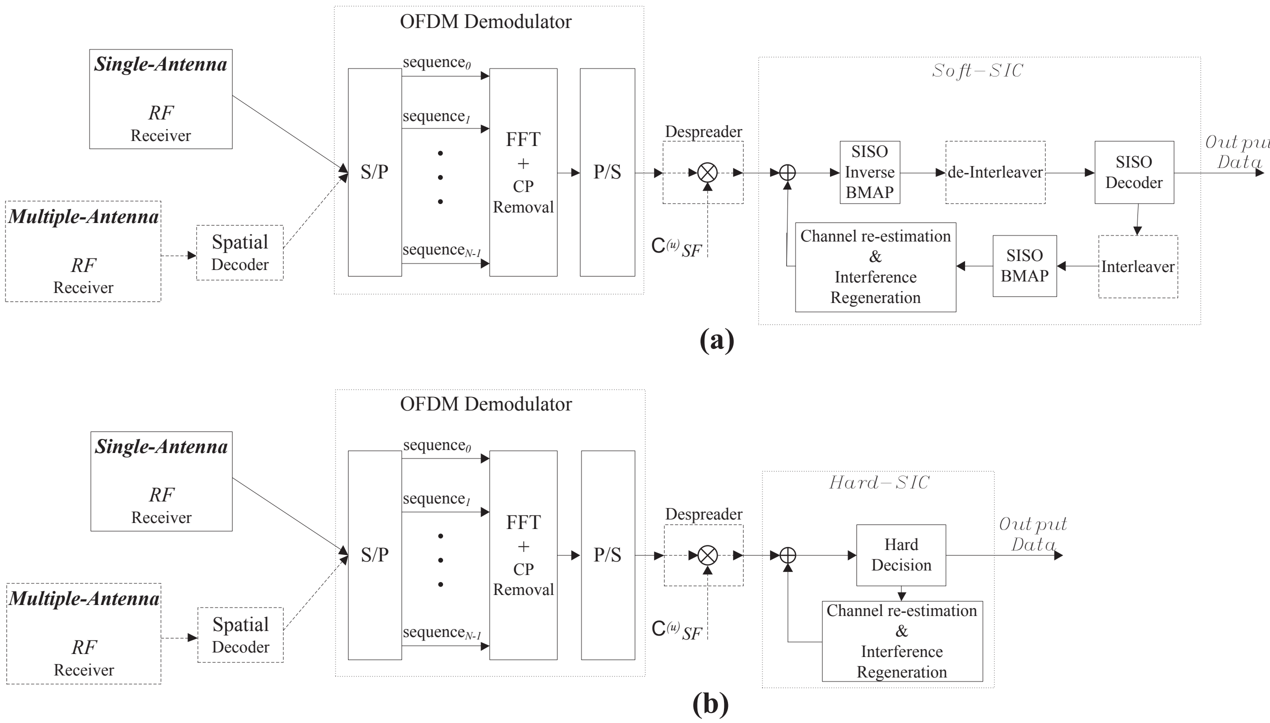

Fig. 3. Block diagram of a typical OFDM SIC-based receiver: (a) Soft-SIC, (b) Hard-SIC. The Interleaver/de-Interleaver and Despreader components indicated by dashed line are present only for BICM and OFCDM receptions respectively. Likewise, the Spatial Decoder and the Multiple-Antenna *RF* Receiver components are utilized only in multiple-antenna infrastructures, which are thoroughly discussed in Section V.

SIC-enabled receivers provide extremely high QoS provisioning in terms of the system robustness and the BER performance, under the fundamental assumption of perfect signal decoding. However, this ideal condition is overoptimistic for realistic network scenarios where the probability of potential errors at the decoding process is quite high. If a symbol is decoded incorrectly, all the subsequent symbols are affected irreparably and the error propagates to all the remaining SIC stages rapidly [18]. Hence, *error propagation* is a crucial parameter for system performance degradation and determines the PCT effectiveness. The limitation of the error propagation represents a major research topic nowadays. In order to suppress the error occurrence probability at each SIC stage, either the simultaneous transmissions from different users or the SIC stages should be upper bounded appropriately. In addition, the decision on the appropriate ordering of the cancelling users plays a significant role for the limitation of the error propagation. The above mentioned solutions are analytically discussed in the next sections with respect to the PCT performance, under both single- and multiple-antenna OFDM infrastructures. Figure 4 gives a representative example of a typical SIC algorithm.

III. Successive Interference Cancellation on Single-Antenna OFDM Systems

Typically, OFDM provides great spectrum efficiency by allowing adjacent subchannels[1] to spectrally overlap, yet remain orthogonal in time [28]. Moreover, the CP addition apart from preventing the ISI effect, it also converts the linear convolution of the data sequence and the impulse response of the channel to a circular convolution [29]. Nevertheless, time variations of the channel within an OFDM frame could still lead to a loss of subcarrier orthogonality resulting mainly in ICI and, thus, to the system degradation. In general, the ICI effect is assumed a random event and, therefore, can be modeled as an additive Gaussian process leading to an irreducible error floor. Subsequently, we show that one of the most crucial factors responsible for the ICI generation is accomplished by the Carrier Frequency Offset (CFO) effect. Thus, we first analyze CFO and we provide SIC-based solutions, afterwards.

[1]The terms subchannel and tone will be used interchangeably in the paper, indicating an OFDM carrier.

A. Interference Enhancement due to the Carrier Frequency Offset

OFDM presents a high sensitivity to the frequency offsets among the subcarriers. CFO along with time variations of the channel are the most crucial effects for ICI realization. CFO is mainly generated either by local oscillator mismatches which cause synchronization errors between the transmitter(s) and the receiver(s) or by the Doppler shift introduced by the user mobility. CFO estimation can be subdivided in two phases, namely *acquisition* and *tracking*. When a user initially enters an OFDM system may experience a large instantaneous frequency offset. An appropriate acquisition algorithm is necessary to detect and correct this CFO initially. After the acquisition phase, the residual CFO is well bounded to a given range (e.g. within a ± 0.5 subcarrier spacing) and the exact CFO

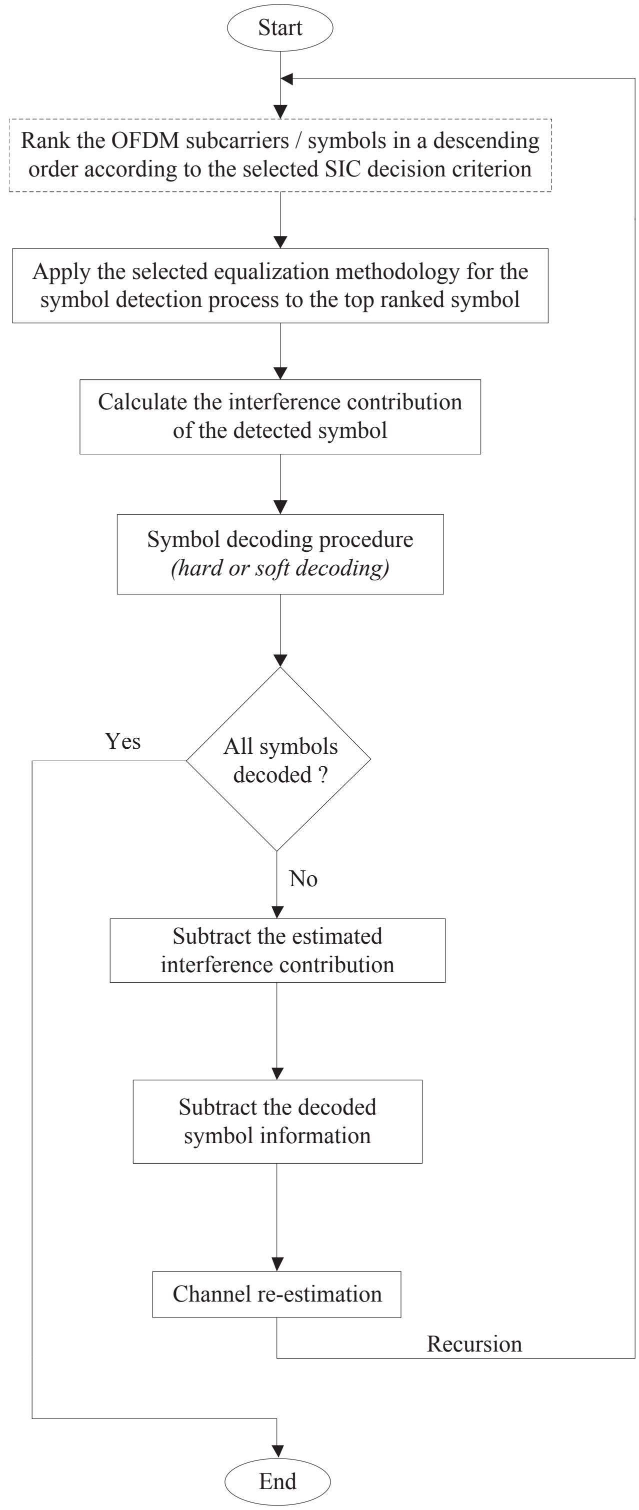

Fig. 4. Flowchart of a typical SIC implementation algorithm. The state indicated with a dashed line is optimal and is used to optimize the BER performance of the overall SIC process.

estimation is then implemented by the appropriate tracking phase algorithm in fixed time instances [30]. Multipath fading, causes multiple received replicas of the transmitted signal to combine destructively, creating a significant probability of severe fades. Multipath fading along with the CFO caused by local oscillator mismatches and the Doppler shift (or spread), constitute the most important parameters that are responsible for interference realization and, more specifically, for the ICI effect in OFDM systems [31].

The ICI can be further extended to self-interference due to the power leakage to other subcarriers of the same user and to the MAI due to the power leakage to subcarriers used for other users transmissions. Especially for OFDMA systems the CFO appearance is unavoidable and, thus, the ICI existence degrades the system performance. For the forward link scenario, mostly in infrastructure-based networks, signals from all the users are multiplexed and sent by the same transmitter (i.e. a base station) appropriately in order to maintain the orthogonality among the subcarriers. MAI can, therefore, be avoided by preserving a tight frequency and time synchronization at the transmitter. In order to reduce the self-interference, each user can perform frequency synchronization between itself and the transmitter by compensating the CFO and, thus, eliminating the total ICI effect. For the more challenging reverse link scenario, however, the MAI effect is present due to the different CFO estimations of the users due to their individual movement with respect to the base station. In this case the CFO estimation and the synchronization constitute a multiple parameter problem and the receivers are not able to restore their CFO according to a reference frequency adjustment as in the forward link scenario. Although self-interference can be eliminated for each user individually, the presence of the MAI component can still lead to the ICI effect. It is worth mentioning that in OFDMA systems, the channel assignment to multiple users is accomplished by three main approaches, namely random, interleaved or clustered schemes. The goal is the diversity maximization over both the frequency and time selectivity of the wireless channel.

There are two methods for the MAI reduction due to CFO in the reverse link case of the OFDM systems, namely *feedback* [32] and *compensation* [33]. Using the former method, the frequency synchronization is accomplished between the transmitter and the receiver with the expense of a high signaling cost and, thus, an overall throughput reduction. The CFOs are fed back from the base station to the multiple users in order to adjust or readjust their frequency offsets. The later method does not require pilot signals for CFO adjustment with the expense of high implementation complexity since advanced signal processing techniques are required [34].

Regarding the compensation method, the use of SIC is found to be beneficial in OFDMA systems especially for the reverse link scenario where the CFO is present, as shown in [33], [35]. By applying SIC techniques in such environments the ICI effect can be eliminated when sophisticated decision strategies are applied. In general, a SIC process can be implemented in a number of stages. At the first stage, symbols are detected and decoded on a per subcarrier basis. Upon a symbol detection, its ICI is also estimated. Afterwards, ICI is reconstructed and then canceled in order to provide better channel conditions for the detection and decoding process of the next symbol and so on.

Nevertheless, if decision errors occur, especially in the first SIC steps, the ICI effect may even worsen. In order to avoid the undesirable later scenario at SIC schemes, the decision ordering should rely on a criterion that satisfies high *confidence* level. Based on that level the symbols are ranked on a descending order according to the detection criterion. The most common detection criterion is the use of the SINR or the signal's power level at the receiver. Hence, the first symbol for detection has the highest confidence level compared to the other ones. In other words it has less probability to create an error floor during the calculation of its ICI component with respect to the other symbols. In [36], the Minimum Euclidean Distance (MED) computation is applied for the detection ordering. More specifically, the authors assumed a *M*-ary constellation while the MED for all symbols is calculated based on the optimal ML criterion as

$$\mathbf{J}_{ML}(n,\widehat{\alpha}_m)=\min_{m=1,\ldots,M}\left|\mathbf{y}_n-\mathbf{G}_{n,n}\widehat{\alpha}_m\right|, \quad (3)$$

where $\mathbf{G}_{n,n}\widehat{\alpha}_m$ is the estimated position of the *m*-symbol, denoted as $\widehat{\alpha}_m$ given a *M*-ary constellation alphabet, as detected at the *n*-th subcarrier, while a hard decision policy has been adopted. The symbol with the less MED has the highest confidence level, thus it is the most reliable for SIC decoding, ICI estimation and then cancellation. The SIC process is not completed until all the symbols in the ordering rank have been decoded. Afterwards, several subsequent SIC stages could follow, where all the subtracted interference information from all the symbols retrieved by the previous stage can feedback accurately the SIC process, resulting to an even better interference cancellation. However, the implementation of several SIC stages increases both the computational complexity and the processing time at the receiver and, therefore, degrades the overall system performance.

B. Complexity Reduction Strategies on SIC Methodology

A novel SIC scheme in [34] outperforms the previously proposed ones by providing low implementation complexity in comparison to the compensate-based strategies, and also because the utilization of a signaling procedure of pilot tones between the transmitter and the receiver is not required. The novelty of this approach is based on the adoption of the IC method on a reliability classification basis in order to compensate CFO and, thus, to reduce MAI, resulting to a total ICI relaxation. The received signals from multiple users are extracted through the use of a hard detection strategy and classified to reliable or unreliable signals, depending on a certain threshold ξ, which is determined by the energy level of the overall received signal. If the signal decisions are above the threshold value in terms of the energy level, they are considered as reliable, otherwise they are considered as unreliable. The former signals are going to participate in the SIC process while the later signals are detected and then decoded by using conventional non-SIC reception techniques after the ICI removal from the reliable ones. The reliability of multi-user signals determines the efficiency of the IC methodology due to the fact that as a signal is more reliable, BER is smaller and, therefore, the signal reconstruction and then the cancellation becomes more accurate. The beneficial results to ICI are, hence, straightforward.

In this scheme, the threshold value plays a crucial role in the system performance. A high threshold value implies a larger number of unreliable signals and, thus, an increased signal distortion probability due to the ICI effect by CFO. A low threshold value on the other hand, enhances the system robustness at the expense of high complexity and high latency due to the higher signal participation in the SIC process. For instance, considering a zero threshold, $\xi=0$ (i.e. all OFDM subcarriers participate in the SIC process), there is a total number of M^N signal cancellations which results in a quite high complexity. Moreover, the appropriate threshold value in [34] is defined through a variety of computer simulations over several OFDM system scenarios. A theoretical study is also implemented in order to validate the performance while a cross-reference analysis shows great convergence between theory and numerical results.

SIC over OFDMA systems with the presence of CFO is also studied in [35]. The authors modeled a very similar system, except that the carrier assignment for the multiple users is implemented by adopting a clustered scheme [37]. More specifically, all the available subcarriers are appropriately grouped to form a certain number of clusters. Each cluster has a fixed number of neighboring subcarriers, i.e. *K* subcarriers per cluster, and each cluster is assigned to a different user. Therefore, the total number of clusters is N/K. An indicative example of this approach is the Partially Used SubChanneling (PUSC) mode of IEEE 802.16e standard, where every four consecutive subcarriers compose a cluster, called *tile* [38]. In such OFDMA systems, the neighboring subcarriers within a cluster are dedicated for a single-user transmission and, therefore, they may suffer from the same (or very close to) amount of fading. Since the detection ordering might not be sorted accurately due to the marginal power difference between the subcarriers within a cluster, a decision error in the signal reconstruction and ICI removal has a great occurrence probability for SIC. As the power level and, therefore, the power leakage to/from these subcarriers is similar, the SIC may not be the appropriate technique to mitigate the ICI effect caused by the self-interference directly [39], [40]. Hence, the authors in [35] proposed an appropriate decorrelator for clustered-based OFDMA systems to efficiently mitigate the self-interference and then applied SIC for further MAI suppression. Using equation (1), matrix $\mathbf{G}$ can be further analyzed into the ICI components and the respective channel coefficients, as the following expression shows

$$\mathbf{G}\equiv\mathbf{\Pi}\circ\mathbf{H}, \quad (4)$$

where $\mathbf{\Pi}$ denotes the $N\times N$ ICI matrix modified by the CFO, $\mathbf{H}$ is the $N\times N$ diagonal matrix containing the channel coefficients and ($\circ$) is the Hadamard product, denoting vector multiplications processed element by element.

Therefore, the corresponding decorrelator is simply implemented by the inverse matrix calculation of $\mathbf{\Pi}$, expressed as $\mathbf{\Pi}^{-1}$. However, as the number of subcarriers is quite large in current OFDM systems, calculating and inverting $\mathbf{\Pi}$ is practically impossible. Considering the self-interference in clustered-based OFDMA systems, the size of $\mathbf{\Pi}$ depends on the size of the cluster, i.e. $\mathbf{\Pi}$ is expressed by a $K\times K$ matrix, where $K<<N$. As the computational complexity is sharply reduced in this case, the authors in [35] implemented the above mentioned decorrelator to mitigate the self-interference ICI. They also assumed that the CFO value for each subcarrier

is an independent and identically distributed (i.i.d.) random variable with zero mean and variance σ_ϵ^2. This is a reasonable outcome since independent random processes can sufficiently represent the stochastic behavior of CFO from one subcarrier to another. Hence, $\mathbf{\Pi}$ has assumed to be a Toeplitz matrix in order to further reduce the overall complexity. From the complexity perspective, arbitrary matrices can be efficiently inverted in $O(K^3)$ computations as compared to $O(K^2)$ for Toeplitz matrices [41]. Moreover, as CFO is assumed to be statistically independent, once $\mathbf{\Pi}$ is calculated and inverted it can be used by all clusters and by all users to further reduce the complexity. The number of total matrix multiplications for the SIC process in [35] is $N(N+K)/2$. After the self-interference mitigation by implementing the above mentioned decorrelator, an appropriate SIC supervenes for the MAI confrontation. In particular, according to the detection ordering on a reception power basis, the first cluster is detected and then decoded by using either hard or soft decision techniques. Afterwards, its MAI component is recomposed and then canceled from the received signal. Then, the detection ordering is re-estimated due to the ICI removal and, thus, due to the power level modification of the remaining clusters, in order to increase the reliability and efficiency of SIC. Thereafter, the same procedure is repeated for the second cluster and so on. In [34], a hard detection strategy is implemented but a soft detection methodology could also be used instead to achieve an even better performance in terms of BER at the expense of the increased processing time and overall complexity.

The authors in [30] also studied the performance of multiuser SIC-OFDM systems in the presence of CFO. They focused on the variance estimation of the CFO for each user with respect to its SINR. A generic carrier assignment scheme was assumed in order to maximize the validity of the proposed work in any OFDM environment while both Gaussian and uniform approximations considered for the CFO activity at each user. More specifically, if CFO is assumed to be a random variable uniformly distributed in the range $(-\epsilon, \epsilon)$, then $\hat{\epsilon} = \sqrt{3}\hat{\sigma}_\epsilon$ where $\hat{\epsilon}$ is the estimated normalized frequency offset and $\hat{\sigma}_\epsilon$ is the maximum estimated deviation for this offset. The maximum offset range for each user's CFO is, therefore, bounded within the interval $(-\sqrt{3}\hat{\sigma}_\epsilon, \sqrt{3}\hat{\sigma}_\epsilon)$. On the contrary, if a Gaussian approximation is assumed, i.e. $\epsilon \sim \mathcal{G}(0, \sigma_\epsilon^2)$, the theoretical range increases to an infinitely large area. Moreover, the probability of a CFO occurrence outside the range defined by the former uniform distribution is 0.0833 [30]. Since most of the realization of frequency offsets fall into this range, the selection of uniform distribution for CFO is efficient enough while it accurately simulates realistic conditions. The SIC adoption in an OFDMA system combined with the variance-oriented frequency estimator proposed in [30] have shown great robustness and efficiency in terms of both BER performance and latency. Particularly, SIC is shown to converge at the second stage while the conventional SIC, i.e. without using the knowledge of the CFO variance, is shown to converge at the fifth stage. This remarkable performance improvement represents an important benefit for reception techniques with high complexity such as the SIC, and testifies that the knowledge of the CFO range is more than a prerequisite for the provision of multi-user IC techniques.

In order to reduce the computational complexity at SIC-OFDM receivers, the authors in [42] proposed a scheme based on MAP detection. More specifically, they extended a previous work [43] which was focused on single-carrier transmission, to multi-carrier systems for multi-user detection. They studied three well known reception diversity techniques for SIC, the Maximum Ratio Combing (MRC), the Equal Gain Combining (EGC) and the Selection Diversity Combining (SDC) and concluded that SDC brings near-optimal results with respect to MRC. In general, MRC has the best performance in terms of BER but also requires high computational complexity. On the other hand, SDC has lower complexity and slightly inferior performance compared to MRC, where the performance of EGC is generally inferior to both MRC and SDC. Their model does not require any pilot signals from the transmitter for channel estimation, in other words it supports blind receiver implementation. In general, blind reception achieves throughput enhancement and delay reduction in comparison to the pilot-enabled transmission/reception, due to the avoidance of signaling overhead, at the cost of the higher BER. Their simulation analysis indicate the slight inferior performance of SDC with respect to the MRC criterion while the adoption of iterative SIC reduces significantly the error floor in comparison to the conventional non-SIC receiver in OFDM systems.

In order to compensate for the ICI effect, MMSE equalization techniques for OFDM receivers have also shown great performance results at the expense of a high computational complexity. Although the classical MMSE equalization shows good performance in terms of BER, in high mobility environments the ICI effect may still occur and, thus, degrade the overall system performance. Hence, MMSE-SIC is found to be beneficial for QoS provision in such environments. The high computational complexity, however, of the linear MMSE-SIC is in the order of $O(N^4)$, [44] while of the classical MMSE is in the order of $O(N^3)$ [20], [44]. PCT is, therefore, more emphatic when MMSE-SIC schemes are applied in OFDM systems. In order to maintain the later tradeoff in a suitable level, authors in [20] focused on the complexity reduction on MMSE-SIC schemes while they tried to preserve their performance.

The MMSE equalizer is expressed as [44], [45]

$$\mathbf{J}_{MMSE} = \mathbf{G}^H(\mathbf{G}\mathbf{G}^H + \sigma^2\mathbf{I}_N)^{-1}, \tag{5}$$

where σ^2 denotes the variance of the frequency-domain AWGN and $\mathbf{I}_N = E\{\mathbf{x}\mathbf{x}^H\}$ represents the identity matrix. Using the signal's power and MMSE, all the received symbols are ranked according to their SINR after a hard detection method has been implemented [20]. As previously mentioned, the detection ordering plays a crucial role to the SIC performance, and upon an MMSE equalization the ordering has to be recomputed at each SIC step, a rather intensive process due to the matrix inversion. The complexity reduction is based on the avoidance of the detection ordering calculation at each step. Instead, the authors relied on the first detection ordering for a whole SIC stage. As the ICI effect is present in the channel matrix, each interference cancellation step may modify the channel coefficients and, thus, the detection ordering criterion. The MMSE-SIC scheme with the later suboptimal ordering is however slightly inferior in terms of BER performance compared to the one with the optimal ordering calculation at each step while its complexity gain can be significantly reduced [20].

To further reduce the complexity, the authors adopted the Sherman-Morrison formula [46] to recursively estimate the inverse matrix of the MMSE equalizer. This formula allows to simply modifying specific matrix row or column coefficients upon a matrix inversion without repeating the whole inversion process from the beginning at each SIC step, as long as the previous inverse matrix state is known (for the detailed algorithm description see [20] and references therein). The MMSE filter is, therefore, calculated at the first step along with the first detection ordering. Thus, for all the subsequent steps the MMSE equalizer is estimated using the above mentioned method and the SIC process is applied on a recursive regime.

The overall computational complexity of the proposed MMSE-SIC in [20] is reduced by a factor of *N*, a significant result in terms of complexity analysis. Moreover, it performs similar to the conventional MMSE-SIC in terms of BER, because the error performance degradation is negligible if the initially optimal ordering sequence (derived at the first SIC step) is used throughout the whole iterations. In more detail, the computational complexity is lower bounded by the use of the IFFT (or FFT) due to the OFDM modulation (or demodulation) which is well known to have a complexity of $(1/2)Nlog_2N$. The upper bound for the computational complexity of the MMSE-SIC in [20] is shown to be $(1/2)N^3 + O(N^2 log_2 N)$.

C. Beyond the Conventional Methods by Introducing Sliced-Processing Window Techniques

By introducing a different perspective, authors in [21] proposed an MMSE-SIC receiver for mobile OFDMA. The appearance of high mobility in such environments results in doubly selective channel fading for the users. The authors focused on the ICI mitigation due to mobility, caused mostly by the Doppler frequency shift (or spread), and their goal was the overall computational complexity reduction in comparison to the previously mentioned studies in this section. As shown in [44] and [47], the effective subcarriers that contribute to the ICI effect in a specific subcarrier are much smaller than the number of all the OFDM subcarriers. The largest ICI contribution in a reference subcarrier is mainly caused by its neighboring ones. Using this fundamental observation, authors in [21] implemented a novel modified linear MMSE-SIC with the aim to reduce the computational complexity of the reception process, while they tried to maintain the BER performance within acceptable levels.

Upon the user signal detection, instead of using the whole channel matrix for the MMSE equalization, they considered only the neighboring matrix coefficients to the reference one. In ideal environmental conditions where the time and the frequency non-selectivity is present, the ICI effect does not appear and, thus, the $N \times N$ channel matrix $\mathbf{G}$ is diagonal. In this case, the computational complexity of the MMSE equalization is $O(N)$, which is the classical motivation for the OFDM usage. Nevertheless, in real conditions the presence of double selectivity results in the ICI occurrence and, hence,

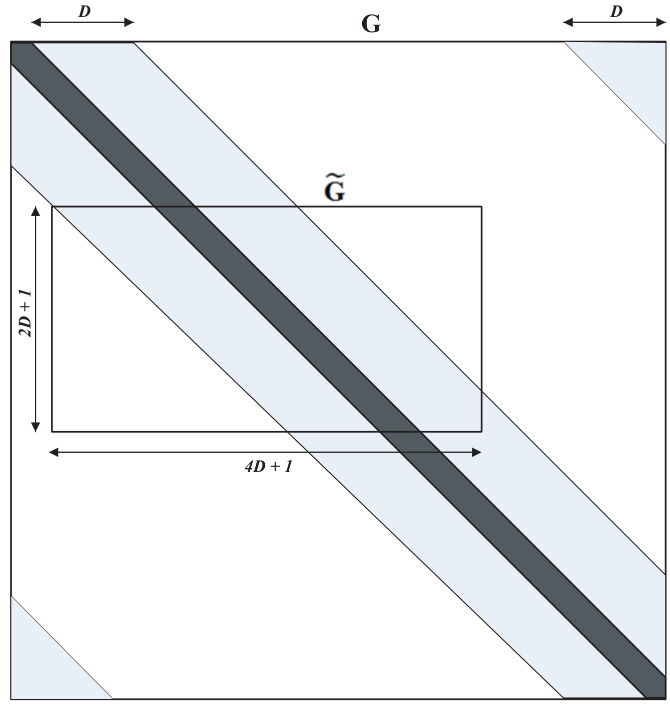

Fig. 5. Structure of the $N \times N$ channel matrix $\mathbf{G}$ and the modified partial channel matrix $\widetilde{\mathbf{G}}$ (redrawn from [21]).

in the existence of non-diagonal channel matrices. The sliced window in [21] for the modified MMSE is formed according to the specified subcarrier distance *D*. The ICI coefficient range is denoted as $2D + 1$, while D is the effective ICI depth that is defined as the half number of significant contributed subcarriers to ICI. A zero-padding process is implemented for the coefficients of $\mathbf{G}$ outside the sliced window since their ICI contribution is assumed to be negligible to the reference subcarrier signal decoding. Exploiting the sparseness of such a channel matrix, the range of the sliced window is chosen to be $(2D + 1) \times (4D + 1)$, as shown in figure 5, which also indicates the dimensions of the modified novel channel matrix $\widetilde{\mathbf{G}}$ [21]. Through excessive computer simulations the authors concluded that the effective distance for *D* in terms of the PCT optimization is 2. In other words, the power leakage due to the ICI effect at a given subcarrier from its four neighboring ones, is not much different to the case where $D = N/2$ (full). This is evaluated using the Matched Filter (MF) bound testing, over several different Doppler frequency shifts, which represents quite an effective strategy, firstly proposed in [48]. As the modified channel matrix is independent of the N OFDM subcarriers, its MMSE equalization has an asymptotic complexity of $O(N)$ [21].

Furthermore, at the conventional SIC process, the MMSE channel equalization is estimated at each SIC step in order to reduce the error floor and to enhance the detection ordering efficiency according to a particular detection criterion, e.g. the signals' SINR. In [21], however, due to the sparseness of the modified channel matrix $\widetilde{\mathbf{G}}$, the selection of the SINR for the decision criterion is a computationally intensive process.

In order to efficiently calculate a user signal's SINR, the knowledge of a *posteriori* power state of all the channel matrix coefficients is necessary. In addition, the calculation of the SINR is generally a large computational burden. Instead, the authors proposed a hard detection scheme. The detection ordering is accomplished according to the signal with the highest channel gain among the undetected data, i.e. the signal with the maximum diagonal coefficient of $\tilde{\mathbf{G}}$. After the first signal equalization, its ICI is reconstructed and then canceled from $\tilde{\mathbf{G}}$ by nullifying its respective column vector. The relaxed channel vector is then re-estimated for MMSE equalization for the second signal detection and so on, until all user signals are decoded. Since the ordering criterion in [21] only requires the finding of the largest diagonal coefficients of $\tilde{\mathbf{G}}$, that is equivalent to the sorting of the N items, and, therefore, the proposed SIC scheme only requires a computational complexity $O(NlogN)$. Thus, as indicated by the PCT factor, a further complexity reduction in comparison to the previously mentioned approaches is accomplished at the expense of a reduced BER performance.

Authors in [49] adopted a similar to the above mentioned strategy for MMSE-SIC receivers over doubly selective channels. More specifically, they applied a sliced window for the MMSE equalization where only the neighboring subcarriers are included for the ICI cancellation, in order to reduce the overall complexity as well as the system latency. Despite the complexity burden of the SINR calculation for MMSE equalization, the authors utilized such a decision metric for the signal's cancellation at each SIC step to enhance the optimality of the decision ordering. As previously mentioned, the decision of the SINR estimation for all the subcarriers within $\tilde{\mathbf{G}}$ is a more complex procedure than only the calculation of the channel gain (i.e. the diagonal coefficient), but on the other hand, provides more reliable and efficient decisions regarding to the signal sorting for SIC. In order to counteract the later complexity enhancement, the authors in [49] reduced the size of $\tilde{\mathbf{G}}$ to $(2D+1)\times(2D+1)$, i.e. the modified MMSE channel matrix becomes a square matrix. Thus, as the complexity of the MMSE equalization increases, due to the more robust decision metric adoption, the channel matrix coefficients are halved with respect to [21], to maintain the overall computational burden at a suitable level. In order to further enhance both the reliability and the robustness of the MMSE-SIC in [49], a soft decision is applied for the signal detection instead of the hard decision applied in [21], for performance improvement. The objective of the soft decision methodology is the reduction of the error floor, especially in the first SIC steps, where there is no initial channel state feedback and also due to the high BER probability mostly because of the signal corruption due to the ICI effect.

In the soft decision process, the error probability of the signal detection is converted to a *priori* LLR. By doing so, the overall BER can effectively be reduced through an iterative process, such as the SIC reception. The simulation results in [49] showed a significant performance improvement with respect to the conventional MMSE-SIC as well as a certain complexity reduction. From the computational complexity perspective, the authors indicated that their scheme requires $O(D^2N)$ operations for the channel equalization in the initial SIC step as well as the same operations in the subsequent SIC steps, contrary to the $O(N^4)$ operations required by the conventional MMSE-SIC reception.

Likewise, the authors in [22] introduced the sliced window technique in their MMSE-SIC over doubly selective channels, by adopting a slightly different methodology though. Their goal was to further reduce the complexity with respect to the above mentioned strategies whereas they tried to maintain the performance in a marginal level in comparison to the conventional MMSE-SIC. They implemented a modified $(2D+1)\times(2D+1)$ square channel matrix $\tilde{\mathbf{G}}$, as in [48], for ICI mitigation via MMSE equalization. Moreover, in order to outperform [49] in terms of computational complexity, they classified the received signals to reliable and unreliable ones, according to a certain threshold ξ, as proposed in [34]. The objective for the later adoption is the relaxation of the overall MMSE-SIC process, since the number of the unreliable subcarriers for decoding is much smaller than all the subcarriers that have been used for MMSE-SIC detection in [21] and [49]. More specifically, the proposed MMSE-SIC equalizer in [22] consists of the subsequent segments. First, the SINR of all the OFDM subcarriers is chosen and estimated-as the appropriate criterion metric-using the channel matrix $\mathbf{G}$, in order to obtain the optimal decision ordering for SIC. Due to the enhanced complexity of the later procedure, the SINR is estimated by taking into account only the diagonal channel matrix coefficients. This approximation is efficient enough since the diagonal coefficients of $\mathbf{G}$ are much larger in magnitude than the off-diagonal ones. Thus, the complexity reduction for the SINR estimation is denoted as $O(N)$ henceforth, while the suboptimality of the detection ordering is unavoidably introduced. This occurs due to the authors' assumption that the ICI channel coefficients do not dramatically affect the SINR prediction achieved by using only the main diagonal coefficients, a rather inadequate decision for realistic scenarios, especially when high user mobility exists.

Nevertheless, the subcarriers are sorted in a descending order and they are divided in reliable and unreliable ones according to a fixed power threshold ξ. This threshold meets the predefined system requirements in terms of the acceptable BER performance, which is obtained by the estimated SINR from $\mathbf{G}$. In the next segment, the classical MMSE equalization is applied only on the reliable subcarriers. Due to the high SINR of the reliable subcarriers, their BER probability is considerably smaller than the unreliable ones and, thus, a linear MMSE equalizer is suitable enough for the efficient detection and decoding without the exigency for the advanced SIC-based reception. Finally, in the same manner, the remaining unreliable subcarriers (or signals) can be detected and then decoded by the modified MMSE-SIC using the relaxed channel matrix due to its sparseness after the nulled channel vectors from the already canceled reliable subcarriers. In addition, in order to further reduce the complexity, the modified channel matrix $\tilde{\mathbf{G}}$ is used for the MMSE-SIC process. As the number of the unreliable subcarriers below the threshold value ξ is denoted as T then the overall computational complexity in [22] is $O(TN)$. Moreover, in order to maintain PCT in acceptable level the authors concluded to the average threshold value, $\xi = \sqrt{N}$. Since $T_{max} << N$, the overall computational complexity is still maintained to $O(N)$.

Unlike the previously mentioned studies, [21], [22] and [49], authors in [50] proposed a novel ZF-SIC scheme based on the same sliced window technique for the channel matrix equalization in order to further reduce the computational complexity. The novelty lies on the use of the ZF equalizer instead of the more complex MMSE at the expense of a slightly inferior BER performance. A ZF equalizer implements the channel matrix inverse operation in order to detect a reference signal. Thus, the estimated signal is obtained as

$$\hat{x} = \mathbf{G}^{-1}\mathbf{y}, \tag{6}$$

where $\hat{x}$ denotes the estimated OFDM symbol derived by a hard decision, $\mathbf{G}^{-1}$ is the inverse channel matrix product derived by the ZF equalizer and $\mathbf{y}$ is the received signal vector. Actually, the ZF equalizer estimates the pseudoinverse product of the channel matrix $\mathbf{G}$, in order to cope with both singular and non-singular matrices, expressed as

$$\mathbf{J}_{ZF} = (\mathbf{G}^H\mathbf{G})^{-1}\mathbf{G}^H. \tag{7}$$

It is clear that the main computational burden in such an equalizer is the inverse estimation in equation (7) which is $O(N^{2.376})$ [51]. Especially in an iterative process as the SIC-OFDM reception, where the complexity increases nonlinearly with the number of subcarriers *N*, the overall computational burden as well as the processing time could reach very high values, inappropriate for practical implementations. A sliced window adoption is, hence, more than a beneficial solution in ZF-SIC receivers [50]. In particular, while the previously mentioned studies, [21], [22] and [49], have focused on a *two-sided* ICI reception, as figure 5 shows, the authors in [50] proposed a *one-sided* ICI reception to further reduce the system latency and the associated complexity. The modified, by the sliced window, channel matrix is, thus, a square matrix with dimensions $(D + 1) \times (D + 1)$. In order to enhance the system efficiency, the authors studied its performance over a challenging environment with high user mobility, to model conditions where the ICI effect becomes quite severe.

The simulation results have shown that the novel ZF-SIC has a very similar performance to the conventional ZF-SIC when $D = 16$ but with only 10% of its computational complexity, which is $O[N(D + 1)^{2.376}]$ [50].

IV. Successive Interference Cancellation On Single-Antenna Spread OFDM Systems

OFCDM (or Multi-Carrier CDMA), which is based on the combination of OFDM and CDMA, has concentrated a great attention and has been widely adopted for high data rate multi-user wireless systems. The need for robust joint coding and modulation schemes is more than a prerequisite in such environments, in order to overcome the effects arising from the time and/or the frequency selectivity. The existence of doubly selective channels leads to bad radio conditions or to high BER probability. Hence, an adaptable to the channel conditions transceiver block for OFCDM systems has to be carefully designed in order to accomplish an acceptable QoS level.

A. Equalization Efficiency and SIC Performance

In [52] a performance comparison of the OFCDM receivers is provided, where three different detection schemes are applied on a per OFDM carrier basis, namely MRC, EGC, and MMSE. MRC superimposes the phase and appropriate weights the amplitude of each subcarrier, while EGC superimposes only the phase of each subcarrier. The role of the MMSE is to minimize the mean squared error between the received and the desired signal. The authors concluded that the most efficient, yet the most complex detection strategy, is MMSE since it takes into account both the channel impact and the noise variance. The most marginal difference with respect to the BER performance was noticed when the MMSE detection scheme was applied.

In addition, when soft equalization is applied on SIC-OFCDM, the BER performance is further enhanced, so as to improve the system reliability. Although a soft decision in a SIC-OFCDM system brings remarkable results to the QoS enhancement in terms of BER reduction and SINR augmentation, it is a quite complicated process. In addition, the error resilience and, thus, the robustness of equalization, is associated with the appropriate SIC detection ordering of the interfering users' signals. The authors in [27] enforced a detection ordering based on the signal power at the receiver. The interferers are ranked according to their degreasing power level. The goal of this detection ordering is that the most important interferers for cancellation, in other words the most important influence for the reference signals degradation, are the ones that reach the receiver with high power. High power of the interfering signals means interference increase and high reference signals corruption probability. In [27], a detection ordering based on the SINR was also enforced, giving however no performance improvement over the power ordering.

Due to the high computational complexity of the soft decision-based SIC, authors in [27] and [53] proposed a soft-Partial SIC (soft-pSIC) where only the interfering users with higher power level than the reference signals power at the receiver are being selected for cancellation. The detection ordering for soft-pSIC is identical to the previously mentioned one with the only difference that the overall interfering signals for cancellation and, thus, the number of SIC stages, have been significantly reduced. In [27], the number of cancelling users in soft-pSIC is on average halved reducing the latency of the system. The performance comparison for both the soft- SIC and the soft-pSIC showed that the former slightly degrades in terms of BER reduction while the later brings reduction in the system latency. Hence, the selection of the appropriate SIC depends on the application where the appropriate PCT level should motivate the choice effectiveness.

B. Coding Effectiveness and SIC Performance

Although convolutional encoders have been thoroughly employed in OFCDM, Serial Concatenated Convolutional Coding (SCCC) brings remarkable performance improvement as well. An SCCC is used at the channel encoder (as shown in figure 1) in [53] for the encoding (decoding) at the transmitter (receiver). SCCCs are built from similar ingredients as turbo codes, but two component encoders are concatenated in a serial fashion. The first component is an outer encoder which uses a non-recursive convolutional code and before it passes the encoded information to the second component, an interleaving process is interposed. Then, an inner encoder using a recursive convolutional code (for better performance) further encodes the data before the transmission. This strategy is implemented softly based on the LLR approximation [54]. SCCCs have shown similar performance to the turbo codes and when combined with SIC at the receiver they perform even better, especially for very low BER requirements (i.e. $< 10^{-5}$) while a large number of iterations can be used. In [53], an MMSE-SIC is used for the first stage where all interferers' signals that exceed the reference signal's power are being canceled. For the subsequent SIC iterations MRC weights are used, since their performance is comparable to MMSE filters for iterative cancellation.

As previously mentioned, the OFDM modulation is equivalent to the multiple flat fading parallel stream transmission in the frequency domain. In addition, OFCDM further enhances the robustness of the former transmission scheme, due to the spreading gain that is employed in order to compensate for the challenging wireless channel conditions. The spreading encoding however equalizes the SINR of each OFDM subcarrier, a rather undesirable scenario for SIC detection schemes at the receiver. Moreover, the spreading sequence at each subcarrier increases the ICI effect. SIC at the receiver is, therefore, more than a prerequisite in such schemes. The power level of each user's signal at the receiver is a fundamental criterion for the detection order sorting and as the SIC is an iterative concatenated process, detection errors are crucial for the decoding efficiency due to the potential error propagation at all the subsequent stages. Hence, authors in [55] proposed a Hybrid OFCDM (HOFCDM) which brings a fragile tradeoff by combining the marginal SINR difference at each subcarrier, a characteristic behavior of the conventional OFDM, and the robustness of the OFCDM encoding. The new hybrid modulator,$\acute{\mathbf{C}}_{\mathcal{SF}}(\theta)$, modifies the spreading matrix accordingly during the spreading process (implemented by the Spreader module as shown in figure 1) and is defined as

$$\acute{\mathbf{C}}_{\mathcal{SF}}(\theta) = \cos(\theta)\mathbf{U}_N + \sin(\theta)\mathbf{C}_{\mathcal{SF}}, \tag{8}$$

where $\mathbf{U}_N$ is an $N \times N$ unitary matrix, $\mathbf{C}_{\mathcal{SF}}$ represents the spreading signature code across the N subcarriers in vectorial form and θ is a tunable parameter.

According to [55], when $\theta = 0$ the overall transmitter is equivalent to the conventional OFDM scheme and when $\theta = \pi/2$ the OFCDM system is obtained. Any other θ value (i.e. $\theta \neq 0, \pi/2$), creates a new kind of diversity and improves the successive non-linear detection process. Furthermore, the above mentioned principle can be extended to any real unitary matrix $\mathbf{U}_N$ verifying $\mathbf{C}_{\mathcal{SF}}^2 = \mathbf{C}_{\mathcal{SF}}^H = \mathbf{U}_N$. The performance results showed that the optimum value for the tuning parameter θ in OFCDM schemes is $\pi/6$ when Walsh-Hadamard (*WH*) spreading signatures are used and a rate $3/4$ convolutional encoding is employed. The performance gain of the SIC-HOFCDM with respect to the conventional SIC-OFCDM reaches 2dB at a BER of 10^{-4}, when an MMSE detection method is adopted.

While the above mentioned studies focused on the adoption of orthogonal spreading coding (e.g. *WH* sequences), authors in [56] and [57] implemented a comparison study of other kinds of precoders including both orthogonal and quasi-orthogonal sequences for OFCDM systems. In particular, except from the use of orthogonal matrix coefficients they also used a certain family of random matrices for the design of the precoder. These matrices consisted of i.i.d. entries. As a particular example and for the sake of implementation simplicity, the coefficients can be chosen randomly from the set $\{1, -1\}$ and the precoder should hold for the following expression

$$\mathbf{C}_{\mathcal{SF}}\mathbf{C}_{\mathcal{SF}}^H = \beta\mathbf{U}_N, \tag{9}$$

where β denotes the average power allocation to each precoder component [57]. It was concluded that a precoder with i.i.d. entries brings a very similar performance to the *WH* precoder as long as $\beta \to \infty$, when MMSE-SIC is applied to an OFCDM receiver.

In the presence of the multipath fading, the MAI effect and the unavoidable existence of the AWGN channel, the contributions firstly in [58] and afterwards in [59] studied the multi-user access in SIC-OFCDM schemes for Ultra- Wide-Band (UWB) applications. In general, in UWB applications the absolute bandwidth is more than 500 MHz. In such environments where high data rates are supported, the presence of the interference is a crucial degradation parameter and SIC-OFCDM schemes perform with high error resilience [59]. The multi-user access can be supported by assigning a different pseudo-random (*PN*) code to each user. The use of *PN* codes, however, intensifies the MAI effect, due to the spreading of the signal and, therefore, there is a need to multiply *PN* codes with *WH* codes before the user assignment signature coding. The orthogonality of *WH* codes reduces the MAI effect while the use of *PN* codes increases the multi-user diversity. The use of these coding strategies jointly stables the above mentioned tradeoff to a suitable multi-user performance, as indicated in [59]. It was shown that when SIC is adapted to the receiver (even though the conventional one, i.e. the hard-SIC), the proposed scheme in [59] outperforms the conventional non-IC OFCDM receiver for UWB applications.

V. Successive Interference Cancellation on Multiple-Antenna OFDM Systems

Future wireless OFDM networks will be driven by high data rate applications and broadband services. Thus, advanced technologies for increasing system capacity and for mitigating the detrimental effects of the wireless and mobile environment are needed in order to support high QoS level and the appropriate error resilience in next generation OFDM-based implementations. Multiple-antenna adaptation holds the premise of achieving significant performance improvement and capacity enhancement in such systems [60]. These techniques transmit a multiplicity of data streams on different antennas simultaneously in order to improve the system capacity and the BER performance. More specifically, multiple-antenna infrastructures are subdivided into

a Single-Input-Multiple-Output (SIMO), where the transmitter side disposes a single antenna element

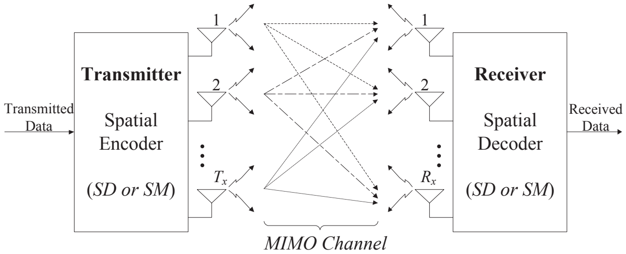

Fig. 6. Block diagram of a typical MIMO transceiver.

and the receiver side disposes multiple antenna elements

b Multiple-Input-Single-Output (MISO), where the transmitter side disposes multiple antenna elements and the receiver side disposes a single antenna element

c Multiple-Input Multiple-Output (MIMO), where both the transmitter and receiver side dispose multiple antenna elements

In this paper, we focus on the MIMO-based platform so as to explore the maximum diversity and performance gain provided by the multiple antenna elements both on the transmitter and the receiver end. Let T_x and R_x be the number of the transmit and the receive antenna elements, respectively. Figure 6 shows a typical representation of a MIMO transceiver. By employing multiple receive antennas, the transmitted data streams can be detected by using the appropriate optimal and/or suboptimal detection schemes. Due to the complementary benefits of MIMO and OFDM, the realization of MIMO-OFDM systems is, therefore, of great importance to ensure both the effectiveness and the reliability of future service demands.

A. Diversity vs. Multiplexing on MIMO-OFDM Systems

In MIMO transmission/reception techniques multipath fading can degrade the system performance more than in the single-antenna techniques and thereby to enforce a tight upper theoretical capacity bound and performance gain. MIMO fading channels can be explored to provide either *Spatial Diversity gain* (SD) or *Spatial Multiplexing gain* (SM) to counteract the later channel impact. The selection of diversity was firstly motivated by the realization of the fading selectivity both in the space and the frequency domain. More specifically, if the distance of the corresponding system antennas is appropriately determined (on the order of a carrier wavelength) or the change in the frequency tones is orthogonal, the fading is an independently changing process [61]. This high selectivity correlation between the space and the frequency domain has found application in MIMO-OFDM systems where the diversity gain can increase the system robustness and reliability, by hedging the transmission's success across multiple realizations in order to decrease the probability of failure.

Pioneered in [62], these techniques have expanded into Orthogonal Space-Time Block Codes (OSTBC) [63] and more than this into space-time codes at large. However, the main drawback of OSTBC is that the orthogonal space-time code for two transmit and one receive antennas is the only OSTBC which is able to accomplish the capacity of a MIMO system [64], since it is not feasible to construct an OSTBC with a transmission rate equal to one for more than two transmit antennas. Hence, Quasi-Orthogonal Space-Time Block Codes (QSTBC) have been proposed which provide transmission rate of one for four and eight transmit antennas, as have been designed in [65], [66] and later generalized to higher number of transmit antennas in [67].

On the other hand, the SM regime was formulated to increase by far the system capacity and transmission rate at the expense of reliability cost due to the lack of transmission diversity adaptation [68], [69]. The main concept in SM is to transmit different symbols from each antenna and have the receiver discriminate these symbols by taking advantage of the fact that, due to spatial selectivity, each transmit antenna has a different spatial signature at the receiver. Thus, if there are T_x antennas, the initial channel capacity or data rate can be further increased to T_x times when a multiplexing gain is appropriately in use. Note, however, that $R_x \geq T_x$ is a prerequisite for SM schemes, whereas multiple receive antennas are only optional for SD schemes [70].

Overall, the selection of either the spatial diversity gain or the spatial multiplexing gain is quite a controversial subject and, thus, the respective Diversity-Multiplexing Tradeoff, namely *DMT*, is a major research topic in modern MIMO-OFDM systems, [61] and [70]-[73]. It has been shown in these works, and more intensely in [61], that in static or quasi-static MIMO-OFDM environments the selection of the multiplexing gain overcomes the diversity one, due to the high probability of the channel non-selectivity, both in time and frequency. In such systems, it is preferable for the robustness provided by the diversity gain to be sacrificed for the actual increased data rate attainment. In high mobility environments, however, where the double selectivity of the channel is present, the diversity gain is more than essential for the potential vehicular system users, whereas the selection of the multiplexing gain in such environments could lead to a rather detrimental performance outcome.

B. ZF vs. MMSE Equalization Performance on SIC-based Receivers

From the interference cancellation perspective, DMT plays a crucial role to MIMO-OFDM system performance. Due to the high computational complexity of the ML detection schemes, most research works focus on suboptimal schemes in order to reduce the system latency, based on either ZF [74][2] or MMSE [75] linear processing for the residue SIC on MIMO receivers. In principle, the ML detection can provide a diversity order which is equal to R_x and independent of T_x [76]. However, space-time codes have a decoding complexity that grows exponentially with the frame length, the constellation size and the number of transmit antennas. Therefore, the authors in [83] focused on the implementation of a ZF-SIC

[2]In fact, ZF in [74] was firstly introduced as a generic IC scheme, but in [75] was treated successively by means of ZF-SIC in order to provide a cross-reference comparison with MMSE-SIC.

receiver for MIMO-OFDM systems in order to significantly reduce the system latency and at the same time to preserve the BER in acceptable levels. Similar to the conventional single-antenna OFDM systems, the ZF detection can eliminate the ICI effect by directly applying the pseudoinverse product of the channel matrix to the received signal transmitted from the multiple antennas. However, the multiple-antenna OFDM systems introduce a two dimensional (joint space-frequency domain) approach for the communication establishment compared to the single-antenna OFDM, which utilize only a one dimensional (frequency domain) approach. In order to efficiently utilize SIC in cumbersome MIMO channel conditions, linear algebraic operations (similar to the previously mentioned single-antenna OFDM) can be accomplished by dealing with the one of the two dimensions, recursively. The most popular regime, followed by numerous research works, is to utilize SIC in the spatial domain with respect to a particular subcarrier and then to repeat this approach at all the remaining subcarriers. In particular, the received signal at the *i*-th OFDM subcarrier can be expressed as

$$\mathbf{y}_i = \mathbf{G}_i \mathbf{x}_i + \mathbf{w}_i, \tag{10}$$

where $\mathbf{y}_i = [y_1, y_2, ..., y_{R_x}]^T$, $\mathbf{x}_i = [x_1, x_2, ..., x_{T_x}]^T$ and $\mathbf{w}_i = [w_1, w_2, ..., w_{R_x}]^T$ are the $R_x \times 1$ received signal vector, the $T_x \times 1$ transmitted signal vector and the $R_x \times 1$ AWGN received vector, respectively. The matrix $\mathbf{G}_i$ denotes the $T_x \times R_x$ channel transfer matrix with $g_{r,t}$, representing the channel gain between the *r*-th receive and the *t*-th transmit antenna. The ZF equalizer can be expressed in an identical fashion as in the single-antenna OFDM system

$$\mathbf{J}_{MIMO-ZF}(i) = (\mathbf{G}_i^H \mathbf{G}_i)^{-1} \mathbf{G}_i^H. \tag{11}$$

It is easily observed that by multiplying the received signal in equation (10) with the later ZF filter, we obtain the ICI-free modified received signal $\mathbf{y}'_i$ expressed as

$$\mathbf{y}'_i = \mathbf{x}_i + \mathbf{w}'_{i,ZF}. \tag{12}$$

In general, the ZF leads to noise enhancement, because the pseudo-inverse channel matrix does not always add destructively and, hence, it could result to the potentially colored additive noise $\mathbf{w}'_{i,ZF}$ at the receiver. Moreover, the diversity gain provided by the multiple receive antenna array for the ICI suppression is eliminated along with the channel matrix coefficients by exploiting the ZF equalizer in MIMO channels, which correspondingly results in a lower overall diversity order.

Due to this essential drawback of the ZF detection strategy, authors in [75] studied the MMSE equalizer instead, expressed as

$$\mathbf{J}_{MIMO-MMSE}(i) = \mathbf{G}_i^H (\mathbf{G}_i \mathbf{G}_i^H + \sigma^2 \mathbf{I}_{R_x})^{-1}. \tag{13}$$

In this case, the ICI is not totally removed by the MMSE equalization in contrast to the ZF-SIC scheme which is able to completely cancel ICI (at the expense of also cancelling the spatial degrees of freedom, available from the receive antennas) [75], [77]. The imperfect ICI cancellation is, however, compensated by providing a higher diversity performance in the decoding process. Moreover, it does not enhance the noise coefficients in comparison to the respective ZF equalization whereas the higher diversity order tenet is found to be more important especially in low SINR system scenarios [75]. In order to counteract the reduction in the BER performance with respect to the ZF, the authors in [75] adopted a soft decision policy based on the LLR symbol approximation at each SIC stage. Furthermore, they also considered an optimal ordering scheme based on a descending SINR level, derived by the trace of the diagonal coefficients provided by the MMSE equalizer at each SIC step. A cross-reference study between the ZF-SIC proposed in [74] and the above mentioned MMSE-SIC, was provided in [75] considering MIMO-OFDM systems with four transmit and four receive antenna elements. The simulation results showed that the later scheme always outperforms the former one, both in low and high SINR regions, in terms of BER at the expense of a slightly increased computational complexity.

C. Complexity Reduction on SIC Methodology

MMSE equalization for MIMO-SIC detectors has received most of the research attention in the last years, due to the error resilience and the high efficiency that preserves. The research community, though, still strives to reduce the computational complexity of such schemes in order to improve the overall system latency combined with high BER performance, especially for the demanding future implementations. Unlike the early research works [78], [79], recent fast MMSE-SIC algorithms [80]-[82] for MIMO-OFDM systems rely on the well-known LDL^H [46], [104] decomposition. The complexity reduction in such schemes is obtained by exploiting the sparseness of the modified channel matrix after the LDL^H decomposition, due to the appropriate use of a union upper triangular matrix $\mathbf{L}_i$ and a diagonal matrix $\mathbf{D}_i$, instead of using the time consuming and more complex full channel matrix $\mathbf{G}_i$ (with respect to the *i*-th subcarrier). To our knowledge, the most efficient scheme achieving the highest PCT balance for the former systems is the one proposed in [82]. More specifically, since BER performance and complexity reduction are two contradict terms (as specified in the introductory section), [82] achieves the highest BER performance by utilizing the lowest computational complexity, compared to the previously mentioned studies. Notice, that both the high BER performance and the reduced complexity are obtained when a SM policy is chosen (in contrast to SD), i.e. when $R_x \geq T_x$, in order to benefit from the multiple transmit antenna elements. Particularly, authors in [82] focused on an equal number of transmit/receive antennas for their simulations, e.g. 4×4 and 6×6 MIMO-OFDM systems. As indicated by the authors, the appropriate detection ordering is crucial for the system performance. They presented either random ordering, or optimal ordering based on the symbols' SNR to their MMSE-SIC scheme. The improved complexity reduction of [82] in comparison to both [80] and [81] relies on a novel two-step LDL^H decomposition process through a series of iterative forward and backward substitutions on the modified channel matrix at each SIC step. In addition, the authors considered two different detection criteria for the optimal detection ordering, namely the Least Mean Squared Error (LMSE) and the SNR upon a signal detection. It was concluded that using LMSE brings both the highest BER performance and the highest computational burden whereas the selection of the SNR is the most effective detection criterion in terms of complexity reduction as the system saves approximately 5.09% complex multiplications at each SIC step compared to the suboptimal random initial ordering.

As previously mentioned, the ML detection scheme has the best BER performance and the highest diversity order, equal to R_x and independent of T_x. Given a constellation size of 2^b symbol points at the received signal with b bits per symbol point, an exhaustive search needs to evaluate all the 2^{bTx} over all the possible symbol vectors to find the optimal solution. The conventional MIMO-SIC (also known as V-BLAST) approach, on the other hand, which is actually a ZF-SIC, provides a significant complexity reduction at the expense of a lower diversity order, especially in the last several SIC steps. More specifically, the selected stream for detection at the first SIC step has a diversity gain of R_x while the stream at the last SIC step has a diversity gain of $R_x - T_x + 1$ [76]. Motivated by the above mentioned diversity-complexity tradeoff at the former schemes, authors in [76] and [83] proposed a hybrid ZF-ML-SIC for MIMO-OFDM systems. They employed a ZF detector for the first SIC steps, where the channel diversity degrees of freedom are quite high, and the optimal ML detector for the last SIC steps where the diversity gains are much lower, in order to enhance both the robustness and the system performance. The proposed SIC scheme has a slightly higher computational complexity in comparison to the conventional ZF-SIC (V-BLAST), due to the partial ML adaption, while it outperforms it in terms of BER. In order to further reduce the overall system complexity, authors in [76] decomposed the channel matrix into the multiplication of two matrices through a QR defactorization, as

$$\mathbf{G}_i = \mathbf{Q}_i \mathbf{R}_i, \tag{14}$$

where $\mathbf{Q}_i$ is a $T_x \times T_x$ unitary matrix and $\mathbf{R}_i$ is a $T_x \times T_x$ upper-triangular matrix. Hence, the received signal vector $\mathbf{y}_i$ is multiplied by $\mathbf{Q}_i^H$ giving

$$\mathbf{y}'_{i,QR} = \mathbf{R}_i \mathbf{x}_i + \mathbf{w}'_{i,QR}, \tag{15}$$

where $\mathbf{w}'_{i,QR} = \mathbf{Q}_i^H \mathbf{w}_i$ is the noise vector after the ZF equalizer modified by the QR defactorization. The reduced complexity for the later expression is evident due to the sparseness of the modified channel matrix $\mathbf{R}_i$. As the diversity gain rendered by $\mathbf{R}_i$ and specified by the respective SIC step is high enough with respect to the given BER requirements of the OFDM system, the modified QR-based ZF-SIC scheme can be used. On the contrary, for the last SIC steps where the diversity gain is reduced, the optimality of the conventional ML-SIC is essential to maintain the error resilience and the overall system efficiency at a suitable level. The simulation results in [76] showed significant BER performance improvement for the hybrid ZF-ML-SIC compared to the classical ZF-SIC, whereas a soft decision criterion based on the LLR approximation is adopted for the OFDM symbol decoding. For each symbol, the soft decision with the largest absolute value is selected and the decoded symbol is computed and then canceled from the residue interference cancellation process for all the subsequent SIC steps. In addition, the SINR is elected as the appropriate criterion for the optimal detection ordering of the SIC process, ranking the columns of $\mathbf{G}_i$ in an increasing manner with respect to their matrix square norms. More specifically, the matrix channel gains with the highest SINR are detected first, because those with a large channel gain may suffer from small interference, whereas it can be a large ICI source to the remaining ones [84].

D. SIC Performance Improvement in the Presence of CRC codes

Authors in [85] proposed a novel implementation methodology for SIC-based detectors at MIMO-OFDM systems. The approach is placed for $T_x = 4$ and $R_x \geq 4$, i.e. for limited number of transmit antennas, in order to relax the MIMO architecture to the scope of practical applications' effectiveness. The information bit streams are isolated in two different data blocks while two transmit antennas are devoted for each block. In fact, the number of data blocks equals to $T_x/2$ for an arbitrary set of an even number of transmit antennas, according to [85, Fig. 1]. Different space-time encoders are enforced for each data block or for each set of transmit antennas. Instead of the joint detection of both blocks simultaneously, which is a very demanding procedure in terms of the computational complexity, a SIC detector has been adopted which handles each block signal separately throughout an iterative processing. Apparently, it detects and then decodes the first data block treating the second one as an interferer and vice versa. In particular, the authors proposed two different kinds of SIC strategies, namely the SIC based on Cyclic Redundancy Check (CRC) and the SIC based on the signal quality. The former approach can be applied on systems in which CRC codes are used for Automatic Repeat and reQuest (ARQ). Since these codes are responsible for the validity of the received data block they can also be used for the SIC process in order to enhance the system reliability. For instance, as indicated in [85], if CRC codes find decision errors, by establishing a hard decision policy, to only one of the two data blocks, the correct block can be detected, decoded and then canceled from the received signal. Hereafter, the previously erroneous signal-without interference from the already canceled correct signal-can be used for detection and then for decoding, which now will have an improved performance.

In [86] a soft decision policy is established for MIMO-OFDM SIC-based receivers when $T_x = 2$ and $R_x \geq 2$, where the soft estimates are iteratively fed back to an interference canceller, allowing for the progressively removal of the mutual interference contribution. On the other hand, the later approach can be applied on systems where CRC codes are not supported. In such systems the block detection can be optimally utilized using the signal quality. The optimal SIC decision ordering in this case can be performed by the MMSE, the SINR, or the SNR criterion. It was shown that the presence of CRC codes brings better BER performance in comparison to the signal quality at the expense of higher implementation cost. Actually, the ordered SIC based on the signal quality decision metric is slightly inferior to the one based on the

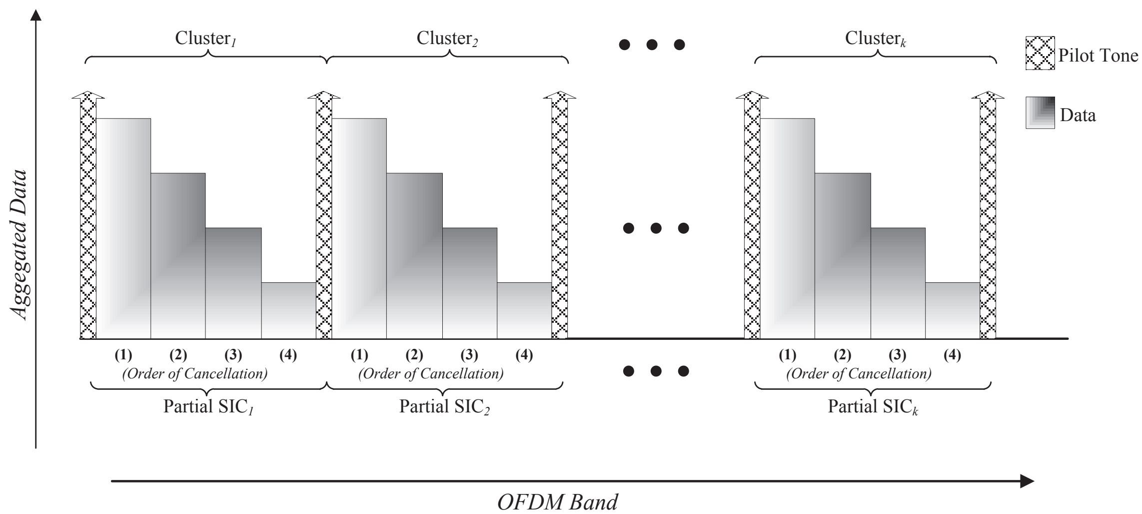

Fig. 7. Typical Example of partial SIC for cluster-based MIMO-OFDM systems.

CRC coding. The performance gap between these two decision metrics reaches a maximum of 1dB on average according to the simulation scenarios in [85] for MIMO-OFDM systems with four transmit and four, six, eight or ten receive antennas. Note that as the number of receive antennas increases the BER performance is also optimized for both decision metrics.

E. Parallel SIC Implementation on MIMO-OFDM Systems

Alternatively, in [87] a different SIC-based reception approach is proposed in order to reduce the system complexity. The authors focused on the ICI mitigation for MIMO-OFDM systems. While the MMSE and the ZF equalization methods can compensate for the interference level to some extent, they, however, cannot guarantee the enough diversity provided by the multiple transmit antennas. In addition, these methods may not perform well enough in doubly selective channels, where the channel suffers rapid time variations. The ML detection method, hence, provides the best performance in terms of both the BER performance and the highest diversity gain but it is unfortunately interwoven with high computational burden at the same time. Apparently, the classical ML-SIC receiver is prohibitive for practical implementations, as previously mentioned, because of the increased overall system latency, especially when MIMO infrastructures are supported. Due to this reason, authors in [87] proposed an approach in which several partial SIC receivers are applied to different OFDM sub-bands separately while they are executed in parallel simultaneously, as shown in figure 7. The iterative SIC process and the parallel SIC execution represent two contradicting terms. In other words, when the SIC detection and decoding process are being implemented on a parallel regime, they may not perform well enough in terms of the effective interference cancellation. The authors, however, solved this problem by applying an ML detection method while they performed a hard decision policy, in order to maintain the complexity in a minimum level. More specifically, they assumed that the whole OFDM band is isolated in clusters of four data subcarriers each and there is a pilot subcarrier between them. An independent SIC is executed in parallel to every cluster. The simulation results showed that the BER performance of the proposed scheme [87] is quite similar to that of the classical ML-SIC while the overall complexity is significantly reduced, at the expense of an overall spectral efficiency reduction. The BER performance depends on both the number of all the OFDM subcarriers and on the cluster size. In [87], a MIMO-OFDM system with 128 tones, two transmit and two receive antennas are used and the achieved processing delay reduction is $[(N/\text{cluster size}) - 1]^{-1}$ in comparison to the conventional SIC.

F. CCI vs. ICI Performance Degradation on MIMO-OFDM Systems

As mentioned in the previous sections, the impact of the interference is one of the most important system degradation factors in OFDM transmissions. This gets more emphatic when multiple transmit antennas and/or multiple receive antennas are used. Moreover, in recent network applications the double selectivity of the considered wireless channel worsens the interference phenomena mostly due to the fast fading and the rapid channel variations in the time domain. More specifically, in the presence of fast fading environments, i.e. where high user mobility is present, the interference effect can be fractioned in two different categories, namely the previously mentioned ICI and the Co-Channel Interference (CCI) [88]. Unlike ICI, which occurs mainly due to the variation of the multipath components within an OFDM symbol transmission period, CCI occurs due to the variation of the CSI values over successive OFDM symbols. When the channel is assumed to be static or quasi-static the effect of the CCI can be considered to be negligible. However, the existence of fast fading conduces to the signal non-orthogonality and the robustness of the OFDM transmission becomes critical.

This behavior has been observed in environments with high mobility since the channel produces rapid time and frequency variations.

Hence, the authors in [88] focused on the CCI suppression in such environments for MIMO-OFDM systems, as the ICI components represent a much less dominant parameter for system degradation, in comparison to the CCI ones, in terms of interference deterioration. More specifically, the CCI power is larger than the ICI power by about 7-8 dB regardless of the channel variation rate [88]. Schemes that adopt a SIC reception method, where the CCI components are detected and then canceled through an iterative process, is found to be beneficial, as it outperforms the conventional non-SIC reception scheme in terms of BER performance at the expense of a slightly increased computational complexity. In addition, in [88] the well-known Alamouti OSTBC encoding scheme is applied for two transmit and one receive antenna elements. It is easy to extend it to an arbitrary number of transmit and receive antennas to provide a larger diversity gain. The improved BER performance of the SIC-based reception scheme compared to the conventional ones is due to the focus on the most dominant CCI mitigation while the ICI is suppressed to some extent by the given diversity gain provided by the MIMO infrastructure.

VI. Successive Interference Cancellation on Multiple-Antenna Spread-OFDM Systems

As indicated in [89], recent advances in Modulation and Coding Rate (MCR) adaptation made feasible to approach the Shannon capacity limit in OFDM systems equipped with single antennas while this capacity limit can be further extended with the aid of multiple antennas. This beneficial feature of the MIMO architecture has attracted considerable research attention, while the more challenging spread version of MIMO-OFDM, which is known in the literature as MIMO-OFCDM (or MIMO-spread OFDM), is considered as one of the most significant technical breakthroughs in contemporary communications [90].

A. Influence of MCR and Transmission Power Adaptation on SIC Performance

SIC methods have been found to be superior to other popular reception implementations when applied on MIMO-OFCDM systems [91], [92]. Performance comparisons between SIC, sphere detector and list sphere detector [93] reception families have been performed. The later two reception strategies utilize the optimal yet quite demanding ML detection criterion. As expected, SIC brings the best performance in terms of computational complexity, throughput and BER performance, especially in high SNR system regions in comparison to the sphere detector families using quite consuming ML criteria and/or MAP probability methods [91].

As in single-antenna OFCDM, in MIMO-OFCDM the transmitted symbols are spread over all the N system subcarriers, which make the quality of each symbol to be appropriately the same in frequency selective channels. When SIC is applied on these systems, the first symbol which is selected for detection, decoding and then IC from the overall received signal, experiences the most dominant BER probability. Since the potential error propagation to the subsequent SIC steps is very crucial phenomenon for the system performance, researchers focused on the joint designation of the appropriate power transmission of each OFDM block and the MCR depth assessment to improve the SIC performance for MIMO-OFCDM systems. In research works [94] and [95], the MCR level is chosen to be the same for each OFDM block while the transmission power varies from one block to another in order to improve the BER performance, as the SIC isolates and detects the symbols more efficiently over different reception power levels. This approach is known as weighted BLAST and has many potential applications in popular current standards [96], [97] and in modern cellular environments [98]. However, in several applications it may not be feasible or desirable to differentiate the transmission power on a per block basis. Due to this reason, authors in [99] and [100] proposed an alternative approach in which the MCR level is adjustable over constant transmission power for MIMO-OFCDM SIC-based receivers. This approach, known as MCR selection BLAST, has many potential applications with reference to prioritizing different data streams for different QoS demands in broadcast scenarios, i.e. by assigning two MCR levels to multimedia codecs, Multimedia Broadcast-Multicast Service (MBMS) and HDTV applications. In general, SIC is a profitable reception technique for MIMO infrastructures as for each OFDM tone which is correctly decoded and then canceled, the received array gains extra degrees of freedom. However, in MIMO-OFCDM each symbol or stream is spread all over the system subcarriers. Hence, there is no applicable solution for symbol isolation and, therefore, for detection on a subcarrier basis.

A rather exhaustive symbol decoding is necessary first at all the system subcarriers before the SIC cancellation at each SIC step. To further enhance the SIC performance, a soft decision policy is supported in [94] and [99] over several numbers of iterations (i.e. turbo decoding), depending on the system requirements before the hard decoding of each symbol. The MCR level adjustment is determined by the target system SINR and by the estimated channel gain at the receiver, e.g. by taking into account the Mean Squared Error (MSE) values on each OFDM stream [101]. Table I shows the appropriate MCR level per spectral efficiency by performing Monte Carlo simulations. It was shown in [99] that the MCR selection BLAST outperforms the respective weighted BLAST strategy in terms of BER performance on MIMO-OFCDM systems, especially when high data rates are supported.

It should be noted that on MIMO-OFCDM systems where each transmit antenna sends multiple symbols simultaneously by assigning different spreading codes to each symbol, a two dimensional interference effect occurs. The Multi-Antenna Interference (MTI) reflecting on the desired signal, due to the transmission of co-channel symbols from other multiple antenna elements and the Multi-Code Interference (MCI) due to the multi-code transmission at the same spatial OFDM tone are observed. Authors in [102] proposed a joint ZF-MMSE-SIC reception method in order to optimize the system BER performance. A ZF equalizer based on QR decomposition is enforced to combat MTI in the space domain firstly and then a MMSE detection to suppress ICI due to MCI and MAI in the frequency domain. A ZF-based detector is considered

TABLE I
INDICATIVE EXAMPLE OF SPECTRAL EFFICIENCY VS. MCR LEVEL IN MIMO-OFCDM (RECAPTURED FROM [99])

Bits/Subcarrier	Stream #	Weighted BLAST	MCR selection BLAST
5.0	1	2/3 QPSK	1/2 QPSK
	2	2/3 QPSK	5/8 QPSK
	3	2/3 QPSK	3/4 QPSK
	4	2/3 QPSK	5/6 QPSK
8.0	1	1/2 16-QAM	3/4 QPSK
	2	1/2 16-QAM	1/2 16-QAM
	3	1/2 16-QAM	1/2 16-QAM
	4	1/2 16-QAM	5/8 16-QAM
16.0	1	2/3 64-QAM	5/8 16-QAM
	2	2/3 64-QAM	2/3 64-QAM
	3	2/3 64-QAM	3/4 64-QAM
	4	2/3 64-QAM	5/6 64-QAM

on both the channel estimation and the signal detection in the space domain, due to its simplicity and its acceptable performance. The QR decomposition reduces significantly the computational burden. The MMSE detector is employed afterwards, enhancing the BER performance at the cost of extra complexity.

Nevertheless, as multiple coded symbols are transmitted at each OFDM tone from each transmit antenna, more than one decision error could occur at each SIC step. Therefore, the authors in [102] have taken into account the correlation between the potential errors at each SIC step by assuming a multivariate Gaussian distribution for the error event modeling. The drawback of this approach is that it becomes intractable as the number of available codes per subcarrier per antenna increases. However, the estimation of the system performance becomes more accurate by taking the error correlation into account at MIMO-OFCDM SIC-based receivers.

B. Parallel SIC Implementation on MIMO-OFCDM Systems

The previous discussion focuses on the SIC architecture in which IC is being implemented sequentially on a per subcarrier basis, by utilizing the same detection ordering to all the N system subcarriers and for all the multiple antenna transmissions. This approach is necessary in MIMO-OFCDM as each symbol is spread at several system subcarriers, depending on the spreading gain and, hence, it is not possible to isolate symbols by utilizing SIC at each subcarrier separately. A rather exhaustive and iterative SIC has to be performed at each system subcarrier and then according to the selected detection metric, the detection ordering is implemented taking into consideration the mean value of each symbol's condition at each subcarrier. Once the detection ordering is decided, SIC is applied on all the subcarriers sequentially whereas the detection, decoding and cancellation process is established based on the initial detection ordering for all the OFDM subcarriers.

Alternatively, in [103] a different SIC architecture is proposed for MIMO-OFCDM systems. The main idea is that several parallel SICs are implemented on different subcarriers (or subcarrier groups) simultaneously, while each SIC detects and decodes the transmitted symbols by adopting different detection ordering in order to exploit both the spatial and the frequency diversities. At least one parallel SIC implements the optimal detection ordering, i.e. according to the received signal's SNR or SINR. All the other parallel SIC approaches are implemented by utilizing a random detection ordering. Moreover, the detection and the decoding of each symbol at each individual parallel SIC is implemented by applying a soft decision policy. The soft outputs from all the parallel SIC approaches are combined utilizing an LLR strategy in order to extract the hard decision for each symbol. It was shown that the proposed scheme in [103] outperforms the conventional SIC for MIMO-OFCDM, whereas the improvement gets more emphatic as the number of both the receive antennas and the parallel SIC approaches increases.

However, as previously mentioned, SIC is a quite complex reception method and as the number of parallel SIC approaches increases, the high system latency and computational complexity becomes unprofitable for practical applications. Additionally, the multiple iterations implemented at the proposed soft detector (turbo detection) endorse the even increased computational burden. Hence, the authors in [103] have only considered relaxed MIMO infrastructures with two transmit and one or two receive antennas in order to maintain the overall complexity within an acceptable level.

VII. Overview & Discussion

In this paper we thoroughly discussed the enviable influence of the SIC reception method on single- and multiple-antenna OF(C)DM systems. The BER performance improvement and the complexity reduction of the reception process represent the major research concerns for SIC provisioning, thereby preserving and optimizing the PCT factor. Since the interference realization is an unavoidable condition in current OFDM systems, there is a growing need for a sophisticated analysis, both theoretical and practical, to optimize SIC-based reception. More importantly, the ICI generation, mostly due to the CFO effect, have encouraged the introduction of advanced signal processing techniques and/or sliced processing window adaptations to SIC methodology. An insight on both these evolutionary enforces was one of the main aspects studied in this paper whereas their adequacy on numerous research approaches meeting different PCT levels was discussed. Particularly, we specified that sliced processing window techniques outperform the conventional (i.e. full processing window) ones in terms of complexity while they are inferior with respect to the BER performance. Moreover, we showed that the typical MMSE-SIC outperforms ZF-SIC in terms of BER performance while introduces an additional computational burden.

Apart from the conventional OFDM, OFCDM has been widely adopted for numerous wireless platforms, either for single- or multi-user applications nowadays [105]. The high-level accuracy and robustness in terms of BER performance, the efficient user QoS differentiation and the optimal multi-user diversity exploitation represent the main reasons for the OFCDM success. Nevertheless, from the receiver side viewpoint, the selection of the appropriate coding strategy affects directly the SIC performance and, therefore, determines the achieved rate in terms of both capacity and performance gain. Most research works are, therefore, focused on either complexity-relaxed SIC implementations or on the joint coding-equalization detection efficiency in order to optimize the reception process for SIC-OFCDM systems. Hence, in this paper we discussed the performance of SIC-OFCDM systems under different coding families and equalization detection techniques with respect to the appropriate PCT level. We also specified that when a hybrid OFCDM methodology is applied on SIC-based reception, the most effective PCT level is introduced. Table II summarizes the most representative SIC approaches for both spread and unspread single-antenna OFDM systems studied in this paper.

Recently, multiple-antenna adaptation has been emerged to achieve both capacity and performance gains in OFDM infrastructures, by introducing MIMO channel parallel transmissions. Nevertheless, MIMO channels can potentially result in significant signal degradation or interference enhancement scenarios. A growing need for a more intensive SIC methodology in comparison to the ones discussed for conventional single-antenna systems is, therefore, one of the most essential presuppositions in order to optimize the reception process. Hence, most researchers strive to balance between the appropriate DMT and PCT depth to approach high data rates and effective BER performance while maintaining the complexity in acceptable levels. Hybrid equalization methods based on ML, MMSE and ZF detection are jointly applied on the SIC reception, in order to exploit the enough diversity provided by the multiple antenna streams. In addition, advanced signal processing techniques are adopted, based on either LDL^H or QR channel matrix decompositions, in order to optimize the SIC process more effectively.

In this paper we also discussed the effective yet quite demanding MIMO-OFCDM SIC-based reception since it provides extra robustness in terms of BER performance at the cost of a slightly higher computational complexity. MIMO-OFCDM provides extra degrees of freedom in multiple access environments by exploiting multi-user diversity and by allowing multi-code transmissions, a rather beneficial feature for current and future user demands. Using spreading sequences, borrowed from the prior CDMA transmission modes, user data are spread to a given range of multiple OFDM tones in order to achieve capacity and performance gain. From the SIC-based reception viewpoint, however, a rather exhaustive symbol detection at each OFDM tone is necessary before every SIC step. Due to the later demanding restriction in terms of complexity, hybrid equalization techniques, as in MIMO-OFDM, are highlighted for SIC-based reception combined with optimal or suboptimal symbol detection orderings, in order to accomplish the appropriate PCT level. Moreover, simultaneous parallel SIC enforcement on different OFDM bands has showed a significant BER performance improvement by exploiting both spatial and frequency selectivity. Unfortunately, the enhanced computational burden of parallel SIC and the extra hardware gear which is necessary makes it unprofitable for MIMO-OFCDM systems with large OFDM tone ranges or high T_x/R_x block arrays. Furthermore, the MCR selection BLAST strategies seem to perform better at the MIMO-OFCDM scenarios, unlike the optimal SIC performance under different symbol power levels, present at conventional unspread MIMO-OFDM systems. Table III summarizes the most representative SIC approaches for both

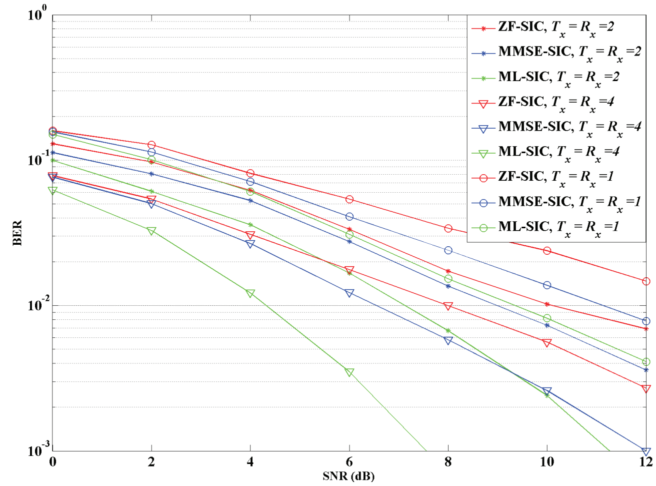

Fig. 8. An illustrative example of the BER performance of various SIC-enabled receivers, when $N = 64$ and the modulation scheme is QPSK. The data rate has remained fixed for both single- and multiple-antenna OFDM systems.

spread and unspread multiple-antenna OFDM systems studied in this paper.

Finally, we have evaluated SIC with respect to the most commonly used equalization methods (e.g. the conventional ML, ZF and MMSE) including both single- and multiple-antenna OFDM systems, by performing typical Monte Carlo simulations. Since the main aspects for the enhancement of the SIC performance are related to PCT, we focus on the BER performance along with the corresponding computational complexity for several SIC schemes. Figure 8 indicates the superiority of ML-SIC in comparison to ZF-SIC and MMSE-SIC for both single- and multiple antenna OFDM systems. It is also obvious that MMSE-SIC slightly outperforms ZF-SIC, at the expense of the higher computational cost as shown subsequently. The SM transmission method is utilized in the multiple-antenna scenario, as an illustrative example. Since the data rate is fixed for all the simulation scenarios, the BER performance gain improves as T_x/R_x increases, as expected, which is an outcome of the spatial diversity gain.

The computational complexity has been evaluated with respect to the number of the expected floating point operations (FLOPs) at each SIC step, by taking into account all the appropriate detection and decoding actions (as shown in figure 4) whereas we have followed a similar methodology as in [106], [107] in order to calculate the number of FLOPs. As previously mentioned, ML-SIC presents an enormously high computational cost which in turn is practically infeasible for OFDM implementations, especially when multiple-antenna infrastructures are employed. Hence, we maintained our focus to a comparison of the most efficient (in terms of PCT level) ZF-SIC and the respective MMSE-SIC while we considered the case of multiple-antenna infrastructures

under QPSK modulation alphabets, as an illustrative example. In order to show the fraction of saved complexity of the conventional ZF-SIC with respect to the respective MMSE-SIC, we introduce the quotient $\xi = \frac{FLOPs_{(ZF-SIC)}}{FLOPs_{(MMSE-SIC)}}$, where $FLOPs_{(ZF-SIC)}$ denotes the number of FLOPs required by ZF-SIC and $FLOPs_{(MMSE-SIC)}$ denotes the number

TABLE II
PERFORMANCE COMPARISON OF SIC METHODS FOR SINGLE-ANTENNA OFDM SYSTEMS

Ref.	**Equalization Methodology**	**Decision Policy**	**Partial SIC**	**Sorting**	**Complexity Optimization** ***(sliced processing window adaptation)***	**Carrier Assignment**	**System SNR (dB)* when BER=** 10^{-2}	**System SNR (dB)* when BER=** 10^{-3}	**# of Users**	**# of** N
[34]	Generic	Hard	Yes	SNR	No	Interleaved	4	6.5	10	64
[35]	MMSE	Hard $O(N)$	Yes	SNR	No	Clustered	17	27	8	256
[36]	ML	Hard	No	SNR	No	Generic	29	-	s.u.****	256
[30]	Generic	Hard	No	SNR	No	Generic	1**	12***	16	256
[39]	MMSE	Soft	No	SIR	No	Generic	4	7	4	64
[40]	MMSE	Soft	No	SIR	No	Generic	7	16	4	256
[20]	MMSE	Hard $O(N^3)$	No	SINR	No	Generic	12	24	s.u.	64
[21]	MMSE	Hard $O(NlogN)$	No	SINR	Yes	Generic	15	23	s.u.	64
[42]	MAP/SDC	Hard	No	LSE	No	Generic	14	20	s.u.	64
[49]	MMSE	Soft $O(D^2N)$	No	SINR	Yes	Generic	8	11	s.u.	64
[22]	MMSE	Hard $O(N)$	Yes	SINR	Yes	Generic	11	22	s.u.	64
[50]	ZF	Hard $O(N(D+1)^{2.376})$	No	SNR	Yes	Generic	14	22	s.u.	64
[52]	MMSE	Hard & Soft	No	SNR	No	Generic	9	14	8	16
[27]	MMSE	Soft	Yes	SNR	No	Generic	-	8	32	64
[56]	MMSE	Hard	No	SINR	No	Generic	7	10	s.u.	256
[57]	MMSE	Hard	No	SINR	No	Generic	7	10	s.u.	256
[53]	MMSE	Soft	No	SNR	No	Generic	5.5	6.2	32	512
[59]	Generic	Hard	No	SNR	No	Generic	6	8	s.u.	2048
[55]	MMSE	Soft	No	SNR	No	Generic	9	17	s.u.	64

*QPSK modulation scheme
**BER= 10^{-4}. The SNR performance for 10^{-2} BER is not applicable
***BER= 10^{-5}. The SNR performance for 10^{-3} BER is not applicable
****s.u. (single-user case study)

TABLE III
PERFORMANCE COMPARISON OF SIC METHODS FOR MULTIPLE-ANTENNA OFDM SYSTEMS

Ref.	**Equalization Methodology**	**Decision Policy**	**Partial SIC**	**Sorting**	**SD vs. SM**	**System SNR (dB) when BER=** 10^{-2}	**System SNR (dB) when BER=** 10^{-3}	T_x/R_x*	**# of** N	Modulation Scheme
[74]	ZF	Hard	No	SNR	SD	13	Not given	4/4	Generic	QPSK
[77]	MMSE	Hard	No	SNR	SM	4	Not given	2/2	Generic	QPSK
[75]	MMSE	Soft	No	SINR	SD	3	4	4/4	256	QPSK
[82]	MMSE	Hard $O(T_x^3)$	No	LMSE & SNR	SD & SM	10	13	4/4	Generic	QPSK
[82]	MMSE	Hard $O(T_x^3)$	No	LMSE & SNR	SD & SM	10	13	4/4	Generic	QPSK
[78]	ZF & MMSE	Hard $O(T_x^3)$	No	LMSE	SD & SM	Not given	Not given	Generic	Generic	Not given
[76]	ML & ZF	Soft	No	SINR	SM	15	23	4/4	Generic	QPSK
[79]	MMSE	Hard $O(T_x^3)$	No	SNR	SD & SM	Not given	Not given	Generic	Generic	Generic
[80]	MMSE	Hard $O(R_x^2)$	No	SINR	SM	3	6	4/4	Generic	QPSK
[81]	MMSE	Hard $O(T_x^3)$	No	SNR	SM	Not given	Not given	Generic	Generic	Generic
[83]	ZF	Soft	No	SNR	SD	10	20	Generic	64	QPSK
[84]	Generic	Hard	No	SNR	SD	4.5	7.8	4/1	64	QPSK
[86]	MMSE	Soft	No	CRC Codes & SNR	SD & SM	18	Not given	2/2	600	16-QAM
[88]	ML	Hard	No	SNR	SD	3.8	7.9	2/2	2048	QPSK
[87]	ML	Hard	Yes	SNR	SD	10	16	2/2	128	QPSK
[91]	MMSE	Soft	No	SNR	SD	25	Not given	2/2	512	64-QAM
[94]	MMSE	Hard	No	SNR & MSE	SD	23	Not given	4/4	1024	16-QAM
[100]	Matched Filter	Hard $O(R_x)$	No	SNR	SD	7	7.9	2/2	Generic	QPSK
[95]	Matched Filter	Hard $O(R_x)$	No	SNR	SD	13	15	2/2	64	16-QAM
[99]	MMSE	Hard	No	Predetermined	SD & SM	21	30	4/4	1024	QPSK
[102]	MMSE & ZF	Hard	No	SNR	SD	12	16.5	4/4	1024	QPSK
[85]	MMSE	Hard	No	CRC Codes & SNR & SINR & LMSE	SM	11	14	4/4	256	QPSK
[92]	MMSE	Hard	No	SNR & SINR & MSE	SD	3	6	4/4	Generic	QPSK
[103]	ML	Soft $O(M^4T_x)$	Yes	SNR & SINR & random	SD & SM	3	6.5	2/2	Generic	BPSK

*All the given performance comparisons have conducted in a single user environment

TABLE IV
COMPLEXITY COMPARISON OF THE CONVENTIONAL ZF-SIC AND MMSE-SIC

$T_x = R_x$	2	3	4	5	6	7	8
ξ	0.86	0.8	0.74	0.7	0.66	0.63	0.60

of FLOPs required by MMSE-SIC. Table IV indicates the complexity enhancement of ZF-SIC with respect to MMSE-SIC, as T_x/R_x increases.

VIII. CONCLUSIONS

Interference cancellation represents one of the most remarkable breakthroughs in modern receiver designs for wireless communication networks. In this paper, we elaborated on the view of SIC clarification, as it is the most effective yet most complex IC scheme for current and future network trends. Since OFDM is one of the most dominant modulation schemes for modern communication designs, the joint SIC-OFDM receiver has strenuously studied over the last years. In order to facilitate the optimization of SIC, we introduced the PCT factor to describe the fragility on the performance improvement and the complexity enhancement of SIC.

We reviewed SIC implementation strategies for single-antenna OFDM infrastructures including both spread (OFCDM) and unspread network applications. These strategies focus on the PCT provision either by implementing advanced signal processing techniques or by adopting sliced-window channel processing methods or by exploiting encoding/decoding procedures effectively.

We also reviewed SIC implementation strategies for multiple-antenna OFCDM and unspread OFDM systems, in order to explore the performance of SIC at all the current multi-carrier network trends. Although advanced signal processing is also adopted for multiple-antenna OFDM receivers, researchers seem to strive for better equalization techniques, composing several detection strategies jointly, unlike the sliced-window adaptations used in the single-antenna scenarios.

We highlighted significant benefits and drawbacks of the SIC process for the above mentioned OFDM systems, throughout an exhaustive analysis provided into this paper. Recent research on SIC-OFDM has made significant strides, but unfortunately more research and development work is necessary in order to prototype SIC-based receivers efficiently and to adapt them to numerous real-world environments. In general, since multiple-antenna infrastructures hold the premise of high-quality services for current and future network applications, SIC on MIMO-OFDM systems should be further improved. The objective of this paper was to provision iterative IC-based reception, by illustrating the state-of-the-art research works so far and to point out some amelioration outcomes, arising from the given performance comparison tables with respect to the PCT level. For instance, sliced-window channel processing has not studied for MIMO-OFDM systems in the appropriate depth so as to exploit from the suitable balance between PCT and DMT factors and, hence, represents one of our future works into the field.

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