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# Analytical Performance Evaluation of Massive MIMO Techniques for SC-FDE Modulations

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**Abstract:** In the Fifth Generation of telecommunications networks (5G), it is possible to use massive Multiple Input Multiple Output (MIMO) systems, which require efficient receivers capable of reaching good performance values. MIMO systems can also be extended to massive MIMO (mMIMO) systems, while maintaining their, sometimes exceptional, performance. However, we must be aware that this implies an increase in the receiver complexity. Therefore, the use of mMIMO in 5G and future generations of mobile receivers will only be feasible if they use very efficient algorithms, so as to maintain their excellent performance, while coping with increasing and critical user demands. Having this in mind, this paper presents and compares three types of receivers used in MIMO systems, for further use with mMIMO systems, which use Single-Carrier with Frequency-Domain Equalization (SC-FDE), Iterative Block Decision Feedback Equalization (IB-DFE) and Maximum Ratio Combining (MRC) techniques. This paper presents and compares the theoretical and simulated performance values for these receivers in terms of their Bit Error Rate (BER) and correlation factor. While one of the receivers studied in this paper achieves a BER performance nearly matching the Matched Filter Bound (MFB), the other receivers (IB-DFE and MRC) are more than 1 dB away from MFB. The results obtained in this paper can help the development of ongoing research involving hybrid analog/digital receivers for 5G and future generations of mobile communications.

**Keywords:** MIMO; mMIMO; SC-FDE; IB-DFE; MRC

## 1. Introduction

With the constant increase in users' needs, in particular, the interconnection of all their communication devices, and its access to the Internet everywhere, the Fourth Generation (4G) of telecommunications has to be rethought. The Fifth Generation (5G) of telecommunications networks arises as a response to existing technology limitations. The 5G network is predicted to have an increase of 10 times in spectral efficiency and 1000 times of system capacity when compared to 4G. It is also expected that this technology is energy efficient [1].

According to the report published by [2], at the end of 2019, about 13 million subscribers to the 5G technology were already expected. In October 2019, right before the official launch of this technology, more than 10 million users have already been registered. Despite the 5G launch ramp, 4G will still be dominant and will reach its peak in 2022, and then it will become superseded by 5G technology. It is also expected that by 2025, 4G will cover around 90% of the world's population, and 5G will cover only 65% of the population but at half of the data traffic. Also, according to the same report, the providers

of this technology are working on a second generation that intends to reduce power consumption, increase frequencies and implement more integrated designs.

The migration to 5G implies new developments in the system design, changes in components and system architecture. One way to achieve these changes is to use massive Multiple Input Multiple Output (mMIMO) [3]. This architecture consists of the existence of multiple antennas in the receiver and transmitter. This implementation allows these systems to have a substantial increase in the data rate and an improvement, not only in energy efficiency, but also in reliability of the connections [1,4].

Channel estimation is one of the limiting factors in this type of system. Another problem is related to the assignment of sequences of finite orthogonal pilots. When the sequences of pilots is reused, it increases the contamination of pilots and coherent interference [3].

With the mMIMO system, the Single-Carrier with Frequency-Domain Equalization (SC-FDE) can be used since this technique allows a lower envelope fluctuation, when compared with Orthogonal Frequency Division Multiplexing (OFDM) [5–7]. SC-FDE allows an efficient power amplification at the Mobile Terminal (MT). In the uplink transmission, the linear Frequency-Domain Equalization (FDE) can be replaced with an iterative FDE on the receiver, such as the Iterative Block Decision Feedback Equalization (IB-DFE) [8]. This replacement leads to an increase in the receiver performance [9].

In the mMIMO system, the number of antennas in the receiver and transmitter increases to tens or hundreds of antennas. This implies the use of large matrices, which is a serious problem in receivers based on the IB-DFE concept [10,11], since this type of receiver requires matrix inversions for each subcarrier and each iteration implies intensive computational processing. Some iterative receivers that achieve similar performance do not require matrix inversions. These receivers can implement, e.g., Maximum Ratio Combining (MRC), which requires the calculation of the hermitian of the channel matrix, or the Equal Gain Combining (EGC) that only needs phase rotations [12,13]. The main problems associated with these low complexity receivers are related to the high interference between different transmitted streams and the Inter-Symbol Interference (ISI).

There are several studies regarding the different receivers that can be used with mMIMO systems [14–17], where the performance achieved is compared with the Matched Filter Bound (MFB). Authors from in [18] propose a hybrid receiver that combines IB-DFE with MRC, achieving performance values similar to MFB in its second iteration.

In this paper, the performance achieved by IB-DFE, MRC, the hybrid receiver and the correlation factor is presented and compared with the theoretical values for the same receiver. The work presented in this paper can be extended to hybrid analog/digital equalization scenarios for massive MIMO systems as presented in [19,20].

In Section 2 the comparison of receivers that can be used in mMimo systems is presented. In Section 3 the proposed system is described and in Section 4 the IB-DFE, MRC and hybrid receivers are presented, followed by Section 5 where the Bit Error Rate (BER) performance and the correlation factors are calculated for the same receivers. In Section 6, the results are presented and discussed. Lastly, in Section 7, the conclusions achieved are drawn.

The following denotation is employed in this paper: In general, the lower case letters denote time-domain variables, while upper case letters denote frequency-domain variables. Bold upper letters represent matrices or vector;  $\mathbf{I}_N$  is the identity matrix  $N \times N$ ; the complex conjugate, transpose and Hermitian of  $\mathbf{x}$  is denoted by  $\mathbf{x}^*$ ,  $\mathbf{x}^T$  and  $\mathbf{x}^H$  respectively. The expectation of  $x$  is represented by  $\mathbb{E}[x]$  and  $\tilde{x}$ ,  $\hat{x}$ ,  $\bar{x}$ , denotes respectively sample, "hard decision" and "soft decision" estimation of  $x$ .

## 2. Receivers

In the literature [14–17] we can find the description of very efficient and appropriate receivers for use in MIMO systems, able to be extended for mMIMO. This section summarizes their main properties.

- ZF: Zero Forcing (ZF) [21] is a simple receiver technique that applies the inverse of the channel frequency response to the received signal to equalize the communications channel. It allows for a perfect separation of the different users as well as the removal of the ISI, however, it cannot be

used in most practical applications as when the received signal is very weak, that is when the Signal-to-Noise ratio (SNR) is very low, it compensates by amplifying the received signal and completely deteriorates the overall SNR when trying to invert values close to zero. In terms of complexity it is not very efficient as well, since it requires the inversion of matrices;

- IB-DFE: The IB-DFE receiver is an iterative receiver where each stream is detected one at a time and the interference is canceled with the help of the streams already detected. When the number of iteration increases, the interference cancellation is improved, improving the overall performance. As with the ZF, this receiver also has the disadvantage of using matrix inversions;
- MRC: The MRC receiver combines the different received branch signals in order to maximize the received SNR ratio. The main advantage is that there are no matrices inversions;
- EGC: The EGC receiver only involves phase rotations, combining all received signals with unitary weights to achieve a high SNR. Like MRC, the EGC does not need matrices inversions.

Table 1 presents a summary of the BER performance achieved by the previous receivers, as well as the number of required iterations to achieve it, where applicable, based on the work presented in [15].

**Table 1.**  $E_b/N_0$  [dB] for the Bit Error Rate (BER) performance of the scenarios presented in [15].

BER	Iteration	MFB	ZF	IB-DFE	MRC	EGC
$10^{-2}$	1	4.2	4.8	4.8	9.1	10.9
$10^{-4}$	4	8.4	—	8.5	—	—

As we can observe, the referred ZF and IB-DFE receivers have the same BER performance as the MFB, for very similar values of  $E_b/N_0$ , remarkably for the IB-DFE. In this table, only the non-iterative versions of MRC and EGC receivers were considered.

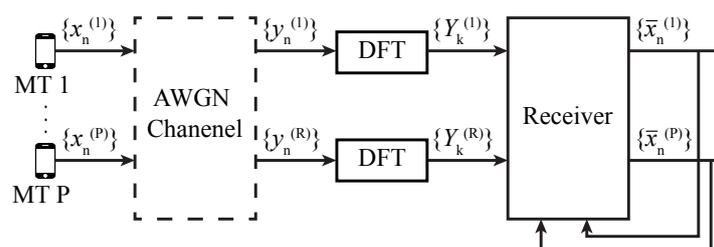
### 3. System Characterization

This paper explores a scenario that implements massive MIMO communications in a highly frequency selective channel and a Single Carrier modulation in the uplink transmission. In this scenario, the communication is established between a MT equipped with  $P$  single transmitting antennas and a Base Station (BS) equipped with  $R$  receiving antennas, with  $R \gg P$  and a perfect synchronization.

In order to remove the ISI, a cyclic prefix, which is larger than the maximum system delay, is added to each transmitted block and removed in the reception side. The MT  $p^{th}$  transmits a block of  $N$  data symbols  $\{x_{n,p}; n = 0, 1, \dots, N - 1\}$  which is received in the  $r^{th}$  BS antenna as  $\{y_n^{(r)}; n = 0, 1, \dots, N - 1\}$  corresponding to a frequency-domain block  $\{Y_k^{(r)}; n = 0, 1, \dots, N - 1\}$ . The  $\{Y_k^{(r)}\}$  block can also be represented in the matrix format  $\mathbf{Y}_k^{(r)} = [Y_k^{(1)}, \dots, Y_k^{(R)}]^T$ , being given by Equation (1):

$$\mathbf{Y}_k = \mathbf{H}_k \mathbf{X}_k + \mathbf{N}_k, \tag{1}$$

where the channel matrix  $R \times P$  for the  $k^{th}$  subcarrier is represented by  $H_k$ , the frequency-domain block of the transmitted block  $x_n$  is represented by  $X_k$  and  $N_k$  represents the channel noise. In Figure 1 the considered scenario is depicted.



**Figure 1.** System scenario.

#### 4. Receivers Design

Since massive MIMO systems are expected to operate with a great number of antennas in the transmitter and the receiver, it is important that the receivers used in these systems have as few matrix inversions as possible. The necessary resources used in matrix inversion increase significantly with the number of entries in that matrix. The greater the number of  $R$  and  $T$ , the higher the associated complexity.

Throughout this section, different iterative receivers based on FDE are presented. In this type of receiver, the estimated signal at the  $i$ th iteration for the  $k$ th subcarrier  $\tilde{\mathbf{X}}_{k,p}^{(i)}$  is given by:

$$\tilde{\mathbf{X}}_{k,p}^{(i)} = \mathbf{F}_{k,p}^T \mathbf{Y}_k - \mathbf{B}_{k,p}^{(i)T} \bar{\mathbf{X}}_{k,p}^{(i-1)}, \tag{2}$$

with  $\mathbf{F}_{k,p}^T = [F_{k,p}^{(1)}, \dots, F_{k,p}^{(R)}]^T$  denoting the feedforward coefficients and  $\mathbf{B}_{k,p}^T = [B_{k,p}^{(1)}, \dots, B_{k,p}^{(P)}]^T$  denoting the feedback coefficients, responsible to reduce the residual ISI after the first iteration.  $\bar{\mathbf{X}}_{k,p}^{(i-1)}$  represents the estimated signal for the previous iteration which is the Discrete Fourier Transform (DFT) of  $\bar{x}_{n,p}$ .  $\bar{x}_{n,p}$  is selected according to a mapping rule, in this case, a Quadrature Phase-Shift Keying (QPSK) with Gray mapping, (i.e.,  $x_{n,p} = \pm 1 \pm j$ ). The average values for  $\bar{x}_{n,p}$ , according to [22], are given by:

$$\bar{x}_{n,p} = \tanh\left(\frac{L_{n,p}^{Re}}{2}\right) + j \tanh\left(\frac{L_{n,p}^{Im}}{2}\right), \tag{3}$$

where

$$L_{n,p}^{Re} = \frac{2}{\sigma_{n,p}^2} \text{Re}\{\tilde{s}_{n,p}\}, \tag{4}$$

$$L_{n,p}^{Im} = \frac{2}{\sigma_{n,p}^2} \text{Im}\{\tilde{s}_{n,p}\}, \tag{5}$$

and

$$\sigma_{n,p}^2 = \frac{1}{2N} \sum_{n'=0}^{N-1} |\tilde{s}_{n',p} - s_{n',p}|^2 \simeq \frac{1}{2N} \sum_{n'=0}^{N-1} |\tilde{s}_{n',p} - \hat{s}_{n',p}|^2. \tag{6}$$

For the first iteration, and since there are no previous iterations, Equation (2) can be simplified to:

$$\tilde{\mathbf{X}}_{k,p}^{(i)} = \mathbf{F}_{k,p}^T \mathbf{Y}_k. \tag{7}$$

Each FDE receiver has different equations for the  $\mathbf{F}_{k,p}$  and  $\mathbf{B}_{k,p}$  coefficients. Sections 4.1, 4.2 and 4.3 present the equations for three distinct receivers.

##### 4.1. IB-DFE

The IB-DFE receiver has already been extensively tested and validated, as mentioned in Section 1. In order to minimize error probability, authors from [11,14,16] define expressions for  $\mathbf{F}_{k,p}$  and  $\mathbf{B}_{k,p}$  coefficients, which are given by:

$$\mathbf{F}_{k,p}^T = \kappa \Lambda_{k,p} \mathbf{H}_{k,p}^H \mathbf{I}, \tag{8}$$

and

$$\mathbf{B}_{k,p}^T = \mathbf{F}_{k,p}^T \mathbf{H}_{k,p}^H - \mathbf{I}, \tag{9}$$

where  $\kappa$  is a normalization parameter ensuring that the overall frequency-response of the "channel plus receiver" for each MT has an average value of 1, i.e.,

$$\frac{1}{N} \sum_{k=0}^{N-1} \sum_{r=1}^R F_{k,p}^{(r)} H_{k,p}^{(r)} = 1. \tag{10}$$

The  $\Lambda$  is given by:

$$\Lambda_{k,p} = \left( \mathbf{H}_{k,p}^H (\mathbf{I}_P - \mathbf{P}^2) \mathbf{H}_{k,p} + \frac{\sigma_N^2}{\sigma_S^2} \mathbf{I}_R \right)^{-1}, \tag{11}$$

where  $\mathbf{P}$  is a diagonal matrix containing the correlation factor between transmitted and detected symbols.  $\sigma_N^2$  and  $\sigma_S^2$  represents the variance of the real and imaginary parts of the channel noise and data samples, respectively.

#### 4.2. MRC

As shown in Section 4.1, the IB-DFE receiver requires the inversion of the channel matrix in the estimation of the received signal. This situation requires too much complexity when moving to an mMIMO system, where there are multiple receiving and transmitting antennas.

As explained in [14,15,17], the MRC receiver combines the different received branch signals in order to maximize the received SNR ratio. In fact, the phases of the received signals are fixed and the conjugate of the channel matrix is used to weight them. The small correlation between the different transmitting and receiving antennas allows us to make the following approach:

$$\mathbf{H}_{k,p}^H \mathbf{H}_{k,p} \approx \mathbf{R}\mathbf{I}. \tag{12}$$

When considering moderate  $R/P$  values, the residual interference cannot be neglected. In order to improve the performance of this receiver, an iterative version should be implemented, such as the IB-DFE receiver. Equation (2) is also considered by this receiver by only changing the feedforward and feedback coefficient equations. Therefore, feedback coefficients are given by Equation (9) and the feedforward coefficients are given by:

$$\mathbf{F}_{k,p}^T = \kappa \mathbf{H}_{k,p}^H, \tag{13}$$

where  $\kappa$  is a diagonal matrix and the element  $(t, t)^{th}$  is given by  $\left( \sum_{k=0}^{N-1} \sum_{r=1}^R |H_{k,p}^{(r,t)}|^2 \right)^{-1}$ .

#### 4.3. IB-DFE Receiver Combined with MRC

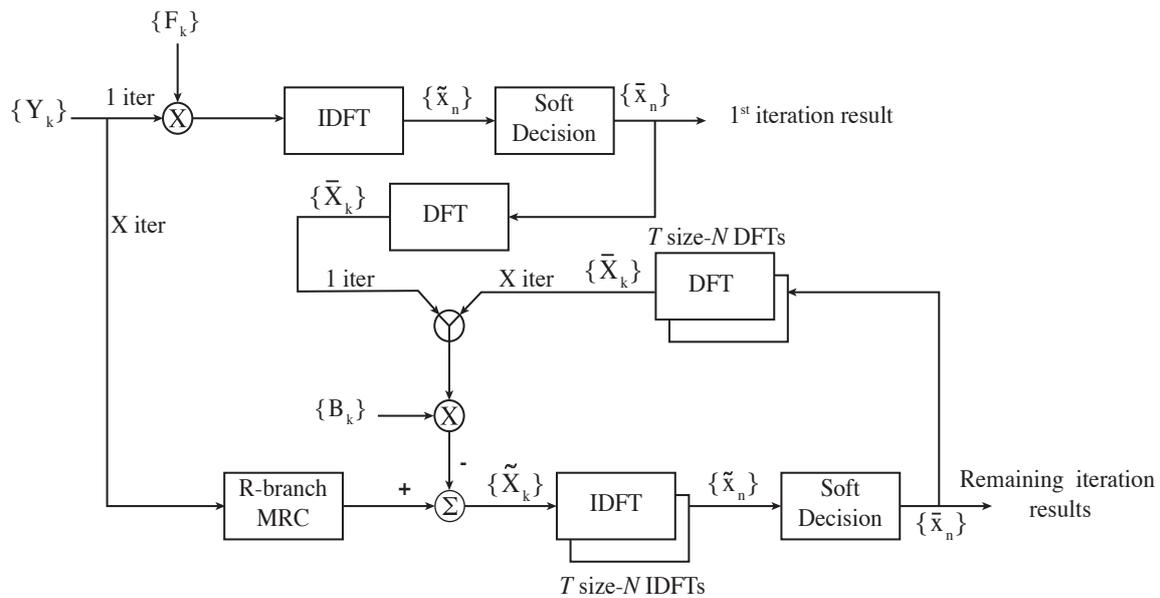
A receiver for mMIMO scenarios was provided in [18] and it reduces the complexity of matrix inversion since it only occurs on the first iteration, achieving performance values very close to MFB at the end of the second iteration. This receiver, in the first iteration, behaves as an IB-DFE receiver and, in the remaining iterations, as the MRC receiver.

The feedforward coefficients are given by Equations (8) and (11), which can be simplified to:

$$\Lambda_{k,p} = \left( \mathbf{H}_{k,p}^H \mathbf{H}_{k,p} + \frac{\sigma_N^2}{\sigma_S^2} \mathbf{I}_R \right)^{-1}, \tag{14}$$

In the remaining iterations, the feedforward and feedback coefficients are given by Equations (9) and (13), respectively.

In Figure 2, the structure of this receiver is depicted.



**Figure 2.** Iterative Block Decision Feedback Equalization (IB-DFE) receiver combined with the Maximum Ratio Combining (MRC) structure.

### 5. Theoretical BER Performance

Each of the receivers presented so far aims to minimize the Mean Squared Error (MSE) which, in turn, decreases BER performance. This minimization takes place through precise selection of feedforward and feedback coefficients. For a QPSK constellation with Gray mapping rule, as considered in this paper, the BER can be calculated by:

$$BER_p \simeq Q \left( \sqrt{\frac{1}{\theta_p}} \right), \tag{15}$$

where  $Q(x)$  represents the Gaussian error function and  $\theta_p$  is given by:

$$\theta_p = \frac{1}{N^2} \sum_{k=0}^{N-1} \Theta_{k,p}. \tag{16}$$

The MSE, represented by  $\Theta_{k,p}$ , can be calculated using:

$$\Theta_{k,p} = \mathbb{E} \left[ \left| \tilde{X}_{k,p} - X_{k,p} \right|^2 \right] = \mathbb{E} \left[ \left| \mathbf{F}_{k,p}^T \mathbf{Y}_k - \mathbf{B}_{k,p}^T \bar{\mathbf{X}}_{k,p} - X_{k,p} \right|^2 \right] \tag{17}$$

As presented in [23] and [11],  $\bar{X}_{k,p} \simeq \rho_p \hat{X}_{k,p}$  where  $\hat{X}_{k,p} \approx \rho_p X_{k,p} + \Delta_{k,p}$  allowing the redefinition of  $\bar{X}_{k,p}$  to  $\bar{X}_{k,p} \approx \rho_p^2 X_{k,p} + \rho_p \Delta_{k,p}$ . In matrix format,  $\bar{\mathbf{X}}_{k,p}$  is given by:

$$\bar{\mathbf{X}}_{k,p} \simeq \mathbf{P}^2 \mathbf{S}_{k,p} + \mathbf{P} \mathbf{\Delta}_{k,p}, \tag{18}$$

where  $\mathbf{\Delta}_{k,p}$  is a mean zero error vector for  $P^{th}$  MT and  $\mathbf{P} = \text{diag}(\rho_1, \dots, \rho_P)$ , with  $\rho$  defined by:

$$\rho_p = \frac{\mathbb{E} \left[ \hat{x}_{n,p} x_{n,p}^* \right]}{\mathbb{E} \left[ |x_{n,p}|^2 \right]}, \tag{19}$$

which, in turn, defines the correlation factor that supplies a blockwise reliability measure of the estimates employed in the feedback loop and associated to the  $(i - 1)$ th iteration [22,24]. For a QPSK constellations,  $\rho_p = 1 - P_e$  and can be approximately given by:

$$\rho_p \approx \frac{1}{2N} \sum_{n=0}^{N-1} \left( \left| \rho_{n,p}^{Re} \right| + \left| \rho_{n,p}^{Im} \right| \right), \tag{20}$$

with

$$\rho_{n,p}^{Re(i)} = \tanh \left( \frac{\left| I_{n,p}^{Re(i)} \right|}{2} \right), \tag{21}$$

and

$$\rho_{n,p}^{Im(i)} = \tanh \left( \frac{\left| I_{n,p}^{Im(i)} \right|}{2} \right). \tag{22}$$

Once the data and noise components have zero mean and are uncorrelated, Equation (17) which represents the MSE can be extended, resulting in Equation (23):

$$\begin{aligned} \Theta = & \mathbf{F}^H \mathbb{E} \left[ \mathbf{Y}^* \mathbf{Y}^T \right] \mathbf{F} - \mathbf{F}^H \mathbb{E} \left[ \mathbf{Y}^* \bar{\mathbf{X}}^T \right] \mathbf{B} - \mathbf{F}^H \mathbb{E} \left[ \mathbf{Y}^* X_p \right] \mathbf{B} - \mathbf{B}^H \mathbb{E} \left[ \bar{\mathbf{X}}^* \mathbf{Y}^T \right] \mathbf{F} + \\ & \mathbf{B}^H \mathbb{E} \left[ \bar{\mathbf{X}}^* \bar{\mathbf{X}}^T \right] \mathbf{B} + \mathbf{B}^H \mathbb{E} \left[ \bar{\mathbf{X}}^* X_p \right] - \mathbf{F}^T \mathbb{E} \left[ \mathbf{Y} X_p^* \right] + \mathbf{B}^T \mathbb{E} \left[ \bar{\mathbf{X}} X_p^* \right] + \mathbb{E} \left[ X_p^* X_p \right], \end{aligned} \tag{23}$$

For simplicity, in Equation (23), the user and subcarrier dependency has been dropped, with the exception for the  $S_p$  factor. We assume:

$$\mathbb{E} \left[ \mathbf{Y}^* \mathbf{Y}^T \right] = \mathbf{R}_Y; \tag{24}$$

$$\mathbb{E} \left[ \bar{\mathbf{X}}^* \bar{\mathbf{X}}^T \right] = \mathbf{R}_{\bar{\mathbf{X}},\bar{\mathbf{X}}}; \tag{25}$$

$$\mathbb{E} \left[ \mathbf{Y}^* X_p \right] = \mathbf{R}_{Y,X_p}; \tag{26}$$

$$\mathbb{E} \left[ \bar{\mathbf{X}}^* X_p \right] = \mathbf{R}_{\bar{\mathbf{X}},X_p}; \tag{27}$$

$$\mathbb{E} \left[ \bar{\mathbf{X}}^* \mathbf{Y} \right] = \mathbf{R}_{\bar{\mathbf{X}},Y} \tag{28}$$

and

$$\mathbb{E} \left[ X_p X_p^* \right] = \mathbf{R}_X. \tag{29}$$

Equation (23), after some manipulation, can be written as:

$$\Theta = \mathbf{F}^H \mathbf{R}_Y \mathbf{F} + \mathbf{B}^H \mathbf{R}_{\bar{\mathbf{X}},\bar{\mathbf{X}}} \mathbf{B} - 2Re \left\{ \mathbf{F}^H \mathbf{R}_{Y,X_p} \right\} + 2Re \left\{ \mathbf{B}^H \mathbf{R}_{\bar{\mathbf{X}},X_p} \right\} - 2Re \left\{ \mathbf{B}^H \mathbf{R}_{\bar{\mathbf{X}},Y} \mathbf{F} \right\} + \mathbf{R}_X. \tag{30}$$

With Equation (30), it is possible to obtain the BER performance through Equation (15) for any of the receivers previously presented.

### 6. Performance Results

In this section, performance results for the three mentioned receivers are presented. For these results, there are different scenarios where the number of transmitting and receiving antennas are changed. Initially, a MIMO scenario with 3 iterations, 4 transmitting antennas and 8 receiving antennas is presented. Then, this scenario is extended to a massive MIMO scenario and the number of antennas was increased 8 times, while keeping the same  $R/P$  ratio and number of iterations.

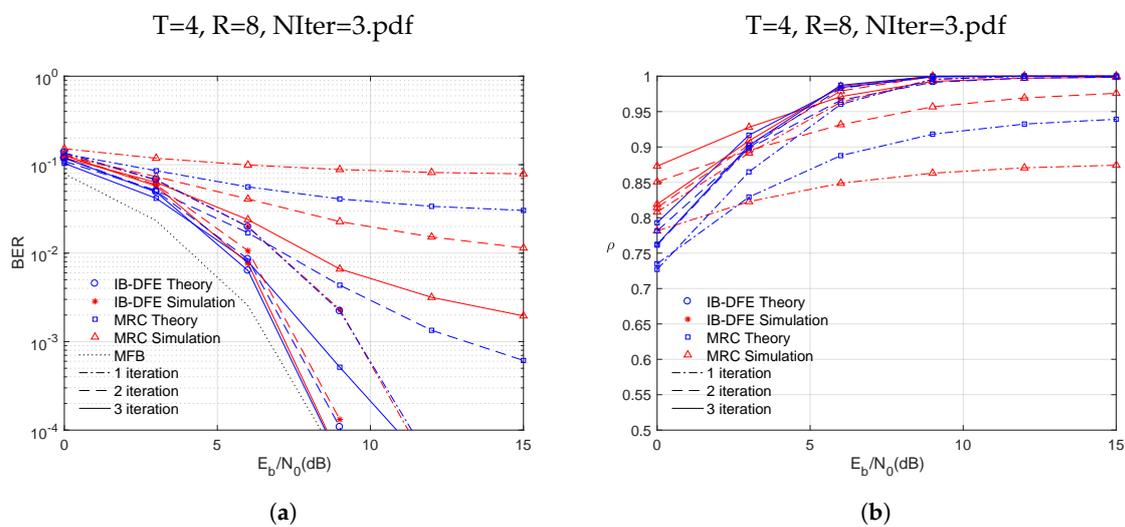
For simulation purposes, it is considered that in each MT,  $P$ , a SC-FDE modulation is applied transmitting 100 blocks with 256 data symbols ( $N = 256$ ), selected from a QPSK constellation under Gray mapping. Perfect synchronization and channel estimation are also assumed.

Performance values are presented as BER values, which in turn is in function of  $E_b/N_0$ , where  $E_b$  is the average bit energy associated with the receiving antennas and  $N_0$  represents the unilateral power spectral density of the Additive White Gaussian Noise (AWGN) channel noise. The lowest bound for the BER performance that a receiver can reach is fixed in the MFB performance which is also presented.

### 6.1. MIMO Scenario

In this scenario, a set of 3 iterations with  $P = 4$  and  $R = 8$  antennas is considered.

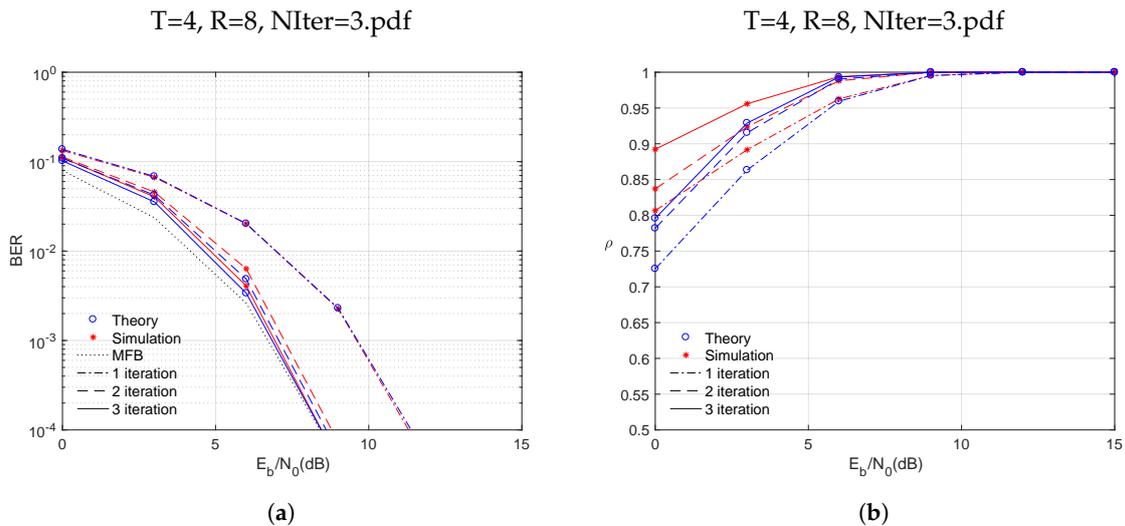
In Figure 3, the theoretical/simulated BER performance for both receivers (IB-DFE and MRC) is depicted in Figure 3a, as well as the correlation factor, shown in Figure 3b.



**Figure 3.** Theoretical/simulated BER performance and correlation factor for IB-DFE and MRC receivers in a Multiple Input Multiple Output (MIMO) system with 3 iterations. (a) BER performance. (b) Correlation factor ( $\rho$ ).

According to Figure 3a, it is possible to verify that the IB-DFE receiver has a BER performance closer to the MFB. In its third iteration, for a BER of  $10^{-4}$ , this receiver presents a difference of less than 1 dB to the MFB. For the same BER, MRC receivers present a worse performance. When comparing the simulated and theoretical values of BER performance, it should be pointed out that the theoretical curves achieve better performance, with the exception of the first IB-DFE iteration where the two curves are identical. In Figure 3b, both receivers, for the first iteration, present values for the correlation factor that never reach the optimum value 1, which implies a worse BER performance, as depicted in Figure 3a. From the second iteration onward, the correlation factor values are close to 1, allowing the achievement of BER performance values close to the MFB.

The performance results of a receiver that combines IB-DFE in the first iteration with MRC in the remaining iterations are depicted in Figure 4. According to Figure 4a, the BER performance of the receiver, in its first iteration is about 3 dB away from MFB and in the remaining iterations, the result approaches the MFB. The theoretical and simulated BER performance values are also very similar. The poor values of BER performance are accompanied by the correlation factor values. As represented in Figure 4b in its first iteration, these values are quite far from the optimal value 1. In the remaining iterations, the value of the correlation factor converges faster to 1.



**Figure 4.** Theoretical/simulated BER performance and correlation factor for a receiver that combines IB-DFE and MRC in a MIMO system with 3 iterations. (a) BER performance. (b) Correlation factor ( $\rho$ ).

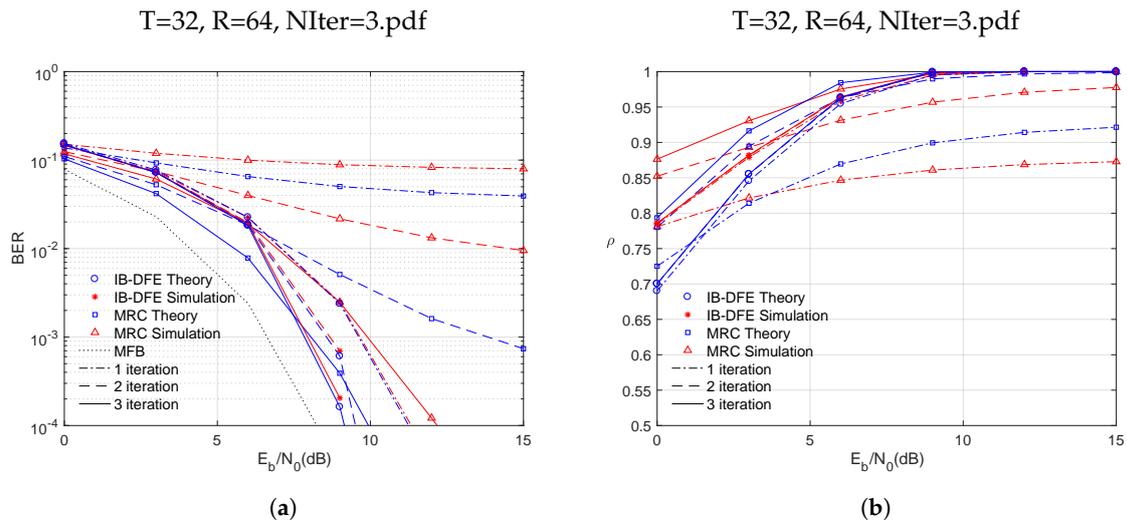
In fact, in the third iteration, this receiver has a difference of 0.5 dB when compared with the MFB, for a BER of  $10^{-2}$  while for a BER of  $10^{-4}$  this difference is reduced to approximately 0.1 dB.

### 6.2. Massive MIMO Scenario

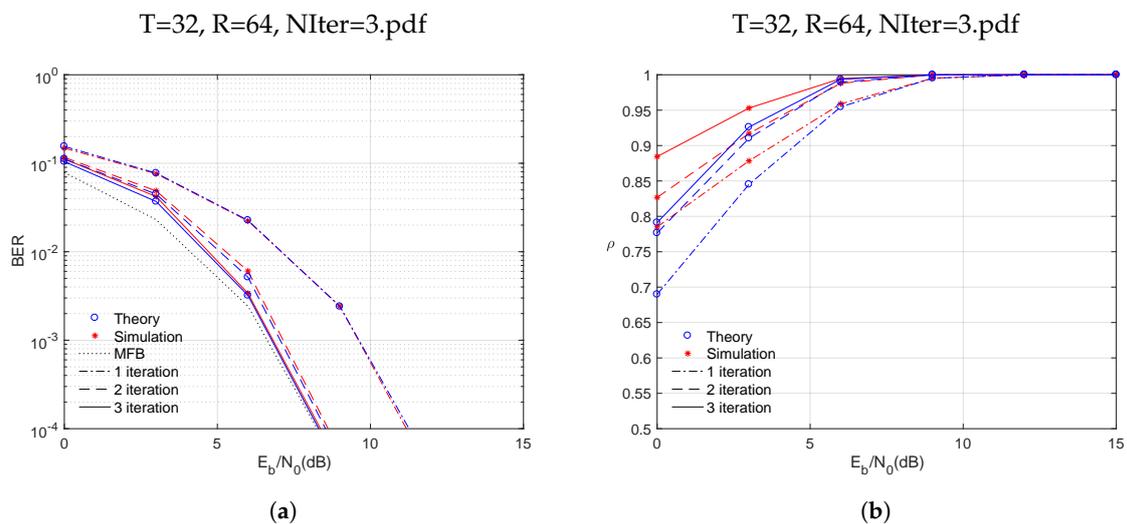
By increasing the number of transmitting and receiving antennas  $P = 32$  and  $R = 64$ , the system can be considered as a massive MIMO system.

Figure 5 shows the performance results for IB-DFE and MRC receivers. As for the MIMO system, the first iteration of the MRC presents weak values as shown in Figure 5a. For a BER of  $2 \times 10^{-4}$ , the simulated value for IB-DFE is 1.2 dB higher than MFB. In the case of MRC, when compared to MFB, the theoretical value is increased by 1.7 dB and the simulated value also increases by 3.8 dB. In Figure 5b the correlation factor is very similar to the one presented in Figure 3b. This is due to the fact that the  $R/P$  ratio is the same.

When analyzing the results for the receiver that combines the IB-DFE with the MRC (Figure 6), the results obtained via simulation practically match with the theoretical values for the BER performance, as shown in Figure 6a. At the end of the second iteration, for a BER of  $10^{-4}$ , the receiver is approximately 0.4 dB away from MFB and in its third iteration, the difference for the MFB is only 0.1 dB. The correlation factor, depicted in Figure 6b in the second iteration of the receiver, for an  $E_b/N_0$  of 5 dB, is practically 1.



**Figure 5.** Theoretical/simulated BER performance and correlation factor for IB-DFE and MRC receivers in an mMIMO system with 3 iterations. (a) BER performance. (b) Correlation factor ( $\rho$ ).



**Figure 6.** Theoretical/simulated BER performance and correlation factor for a receiver that combines IB-DFE and MRC in an mMIMO system with 3 iterations. (a) BER performance. (b) Correlation factor ( $\rho$ ).

## 7. Conclusions

This paper presents the study of FDE-type receivers that can be used in massive MIMO systems. The structures of three receivers, where the complexity depends on the estimation of the received signal, are discussed.

The BER performance of these receivers is simulated and compared with theoretical values. The impact of the correlation factor on BER performance is also studied.

One of the receivers propose in this paper is a receiver that combines, in its first iteration, the IB-DFE receiver and in the remaining iterations the MRC receiver. The BER performance achieved by this receiver, in massive MIMO scenarios, is only 0.1 dB away from the MFB, in its third iteration, and the simulated/theoretical values match very closely.

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