Performance Evaluation of Low-complexity Receivers for MIMO Underwater Spatially Correlated Channels

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Abstract— This paper shows that low-complexity combining techniques such as Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC) can be employed with multiple input multiple output (MIMO) systems applied to underwater acoustic (UWA) communications. This brings added value thanks to the low-complexity receivers and efficient processing, while achieving a good performance, even in scenarios with correlation between antennas.

1. INTRODUCTION

Underwater wireless communications have received increasing attention in recent years. One of its main challenges is the low bit rates, which are closely linked to the superimposed underwater channel, experienced in very adverse conditions [1]. To mitigate these adverse conditions, MIMO systems were adopted. However, exploiting the capacity and diversity gains associated with MIMO systems, it is conditioned by the existence of spatially uncorrelated channels [2]. Nevertheless, this condition is rarely fulfilled in underwater scenarios, where the multipath is low and the low frequencies of the carrier require a large spacing between the antennas. Consequently, in underwater scenarios, the most common implementation presents a certain level of correlation between signals of different antenna elements.

In recent years, augmented MIMO systems (massive MIMO [m-MIMO]) have been proposed to further increase the gains associated with traditional MIMO [3]. However, the large number of antennas that these systems present poses great demands on the complexity of signal processing, so the use of sub-optimal receivers such as EGC or MRC is decisive [4, 5].

The low-complexity receivers based on MRC and EGC presented in this paper are compared and studied in underwater scenarios, using a MIMO communications system, assuming both uncorrelated channels and different levels of correlation between signals of antenna elements, and using Single Carrier Frequency Domain Equalization (SC-FDE) transmissions [4]. Afterwards, the results are evaluated, compared, and then commented, to support a possible implementation of a UWA communication system.

This paper is organized as follows: Section 2 presents the signal model associated to SC-FDE transmissions; Section 3 describes the structure for the Proposed MIMO and Associated Receivers based on the EGC and MRC; Section 4 analyzes the performance results and Section 5 concludes the paper.

2. SIGNAL MODEL

The complexity of underwater acoustic medium and the low propagation speed of sound in water, makes the underwater acoustic channels commonly regarded as one of the most challenging channels for communications. The only way to implement the simulation of the present study was to include the channel impairments and adversities in the code, and therefore, creating a system that resembles the outputs of a real-world application. Our algorithm emulates the propagation channel [2].

In Orthogonal Frequency Division Multiplexing (OFDM) the original bandwidth is divided into multiple subcarriers. Each of this subcarrier can them be individually modulated [6].

OFDM is mainly used in downlink, but it presents a high Peak-to-average Power Ratio (PAPR), so it is not well suitable for to low power and low complexity transmitters. In this scenario, SC-FDE transmissions are a better choice, which benefits from a single carrier multiplexing by having a lower PAPR. On SC-FDE transmissions, before applying the Inverse Fast Fourier Transform (IFFT), the symbols are pre-coded by a Discrete Fourier Transform (DFT) so each subcarrier after the IFFT will contain part of each symbol.

The transmitted block can be considered as:

$$x\left(t\right)=\sum_{n=-N_G}^{N-1} x_n h_T\left(t-nT_S\right), \tag{1}$$

where T_S denotes the symbol duration, N_G the number of samples at the cyclic prefix while $h_T(t)$ is the adopted pulse shaping filter. Moreover, the signal $x(t)$ is transmitted over a time-dispersive channel and the signal at the receiver input is condensed and sampled, and the cyclic prefix is removed, transforming to the time-domain block $\{y_n;\ n=0,1,\ldots,N-1\}$. In SC-FDE schemes, the time-domain block to be transmitted is $\{x_n;\ n=0,1,\ldots,N-1\}$, denoting the length-$N$ data block to be transmitted, where x_n is the nth data symbol, selected from a given constellation, under an appropriate mapping rule (it is assumed that $x_{-n}=x_{N-n}$, $n=-N_G,-N_G+1,\ldots,-1$). The transmitter frequency-domain block is $\{X_k;\ k=0,1,\ldots,N-1\}=DFT\{x_n;\ n=0,1,\ldots,N-1\}$.

Reckon that the cyclic prefix is longer than the overall channel impulse response of each channel, the frequency-domain block after the FDE (Frequency Domain Equalization) block (i.e., the DFT of the received time-domain block, after removing the cyclic prefix) is $\{y_n;\ n=0,1,\ldots,N-1\}=IDFT\{Y_k;\ k=0,1,\ldots,N-1\}$, with

$$Y_k=X_kH_k+N_k \tag{2}$$

where $\{H_k;\ k=0,1,\ldots,N-1\}=DFT\{h_n;\ n=0,1,\ldots,N-1\}$ denotes the channel frequency response for the kth subcarrier (the channel is assumed invariant in the frame) and N_k is the frequency-domain block channel noise for that subcarrier.

We assume the frame structure with N subcarriers per block and N_T time-domain blocks, each one corresponding to an "FFT block".

The conventional linear FDE for SC (Single Carrier) schemes comes,

$$\tilde{X}_k=\left[Y_kH_k^*\right]\beta_k^{(2)} \tag{3}$$

where $\beta_k^{(2)}=(\alpha+(|H_k|^2))^{-1}$. As expected,

$$\tilde{X}_k=X_k\left|H_k\right|^2\beta_k^{(2)}+N_k^{eq} \tag{4}$$

In addition, we define $\alpha=E[|N_k|^2]/E[|X_k|^2]$. N_k^{eq} denotes the equivalent noise for detection purposes, with $E[|N_k^{eq}|^2]=[2\sigma_N^2|H_k|^2]\beta_k^{(2)}$, and with $\sigma_N^2=E[|N_k|^2]/2$.

3. STRUCTURE FOR THE PROPOSED MIMO AND ASSOCIATED RECEIVERS

The MIMO scenario depicted in Figure 1 is adopted, consisting of a transmission using T transmit antennas and R receive antennas.

3.1. Computation of the Processing Coefficient

As defined in Section 2, SC-FDE modulations are employed. We assume that $R\gg T$. The tth transmit antenna has a block of N data symbols $\{x_n^{(t)};\ n=0,1,\ldots,N-1\}$ to send. The received block is $\{y_n^{(r)};\ k=0,1,\ldots,N-1\}$. The frequency-domain block $\{Y_k^{(r)};\ k=0,1,\ldots,N-1\}$ satisfies

$$\mathbf{Y}_k=\left[Y_k^{(1)},\ldots,Y_k^{(R)}\right]^T=\mathbf{H}_k\mathbf{X}_k+\mathbf{N}_k \tag{5}$$

where $\mathbf{H}_k$ denotes the $R\times T$ channel matrix for the kth frequency, with (r,t)th element $\mathbf{H}_k^{(r,t)}$. The transmitted symbols comes $\mathbf{X}_k=[X_k^{(1)},\ldots,X_k^{(T)}]^T$.

Let us consider the frequency domain estimated data symbols $\tilde{\mathbf{X}}_k=[\tilde{X}_k^{(1)},\ldots,\tilde{X}_k^{(R)}]^T$.

1. For the Zero Forcing (ZF) Receiver, the data symbols can be obtained from the Inverse Discrete Fourier Transform (IDFT) of the block $\tilde{\mathbf{X}}_k$, where [4]

$$\tilde{\mathbf{X}}_k=\left(\mathbf{H}_k^H\mathbf{H}_k\right)^{-1}\mathbf{H}_k^H\mathbf{Y}_k \tag{6}$$

2. Using the MRC receiver, $\tilde{\mathbf{X}}_k$ comes:

$$\tilde{\mathbf{X}}_k = \mathbf{H}_k^H \mathbf{Y}_k \tag{7}$$

where R stands for the number of receiving antennas.

3. Using the EGC receiver, $\tilde{\mathbf{X}}_k$ comes:

$$\tilde{\mathbf{X}}_k = \exp\left\{j \arg\left(\mathbf{H}_k^H\right)\right\} \mathbf{Y}_k \tag{8}$$

While the ZF requires the computation of inverse of channel matrix for each frequency component of the channel, the MRC and the EGC do not require such computation, making it simpler. A disadvantage of the MRC and EGC relating to ZF relies on the generated interference, which degrades the performance. In order to improve the performance, we consider an iterative receiver, as defined in the following.

3.2. Interference Cancellation Using Post-processing

Since the post-processing approach considers the processing at the receiver side, the detector computes the data symbols obtained from the IDFT of the block $\{\tilde{X}_k^{(r)};\ k = 0, 1, \ldots, N-1\}$ with:

$$\tilde{\mathbf{x}}_n = IDFT\left(\tilde{\mathbf{X}}_k\right) \tag{9}$$

The estimated bits are obtained by applying the sign function to $\tilde{\mathbf{x}}_n$, depending on the modulation scheme.

In the case of ZF receiver, this involves the inversion of a matrix for each frequency component, and the dimensions of these matrices can be very high, especially in massive MIMO systems. MIMO schemes should usually employ simpler receivers. The simplest approach is probably to employ the MRC or EGC. This takes advantage of the fact that, for massive MIMO systems with $R \gg 1$ with small correlation of the channels between different transmit and receiving antennas, the elements outside the main diagonal of

$$\mathbf{A}_k^H \mathbf{H}_k \tag{10}$$

are much lower than the ones at its diagonal, where (i, i')th element of the matrix $\mathbf{A}$ are defined as:

1. For MRC: $[\mathbf{A}]_{i,i'} = [\mathbf{H}]_{i,i'}^H$.
2. For EGC: $[\mathbf{A}]_{i,i'} = \exp(j \arg([\mathbf{H}]_{i,i'}))$, i.e., they have absolute value 1 and phase identical to the corresponding element of the matrix $\mathbf{H}$.

For SC-FDE signals we could employ a frequency-domain processing with MRC or EGC at each frequency, based on $\mathbf{A}_k^H \mathbf{H}_k$. However, the residual interference levels can still be substantial, especially for moderate values of R/T. To overcome this problem, we propose the iterative interference canceller (receiver) depicted in Figure 1(b), where

$$\tilde{\mathbf{X}}_k = \mathbf{A}_k^H \mathbf{Y}_k - \mathbf{D}_k \bar{\mathbf{X}}_k \tag{11}$$

The interference cancellation matrix $\mathbf{D}_k$ comes defined by

$$\mathbf{D}_k = \mathbf{A}_k^H \mathbf{H}_k - \mathbf{I} \tag{12}$$

where $\mathbf{I}$ is an $R \times R$ identity matrix.

This interference canceller is implemented using $\bar{\mathbf{X}}_k = [\bar{X}_0, \ldots, \bar{X}_{N-1}]$, with $\bar{\mathbf{X}}_k$ denoting the frequency-domain average values conditioned to the FDE output for the previous iteration, as defined for the precoding in [7].

4. PERFORMANCE RESULTS

In this section, we discuss the experimental results obtained with the Monte Carlo simulations. Simulations were made for the MRC, EGC and ZF, with the MIMO configuration and underwater propagation channel, aiming to evaluate the performance of the low complexity receivers.

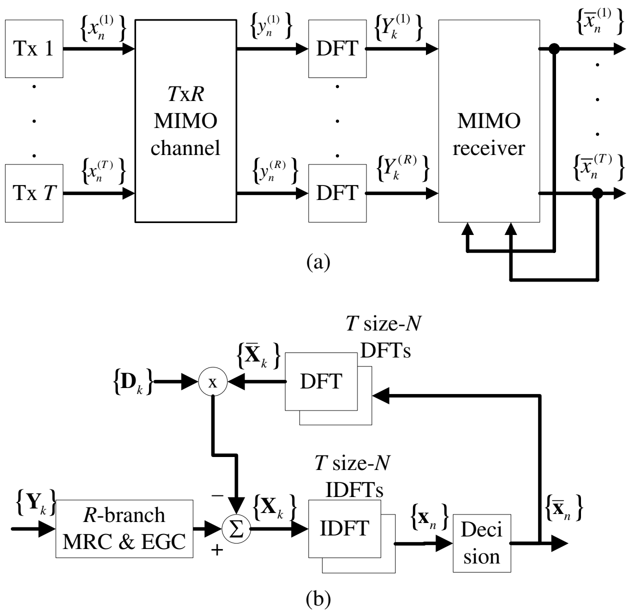

Figure 1: Block diagram of MIMO, (a) using SC-FDE, (b) details of MIMO receiver and interference cancellation.

It was described that the MRC and EGC receivers are very simple. Nevertheless, a certain residual interference exists. Therefore, the iterative receiver presents an interference cancellation that aims to mitigate it (with one two or four cycles of interference cancelation).

It is worth noting that an increase in the number of transmitting antennas results in an increase of the symbols rate. Moreover, increasing the number of receiving antennas results in an increase of diversity and, as a result, on a performance improvement. Apart from the EGC and MRC, the Matched Filter Bound (MFB) curve is a way to measure the channel modeled by the sum of delayed and independently Rayleigh-fading rays. Briefly, if two rays of a channel have comparable average powers, and if the delay spread is moderate or large, then a considerable diversity gain can be obtained. It works as if the two rays could be detected separately and their results combined. Under these conditions, for the sake of comparison, the MFB are included in all simulations, since it is a reference that points out to the best possible performance indicator. To be noted that T stands for the number of transmitting antennas and "R" for the number of receiving antennas. Furthermore, L denotes the number of cycles of interference cancelation (1, 2 or 4) [4–6].

Figure 2 shows a MIMO system with 2 transmitting antennas and 4 receiving antennas. EGC with $L = 4$ iterations of interference cancellation attained the best performance results, slightly worse than the MFB performance reference. Here is a typical case in which we have $R > T$, and so a diversity gain exists, and therefore less interference but a slightly worse symbols rate. Both, the MRC and EGC, without interference cancelation, achieve poor results in this MIMO configuration. Under this configuration, the best performance results are achieved by the EGC, with 4 iterations of cancellation. It is worth noting the EGC is even simpler to implement that the MRC. Of course, the 4 iterations will worsen the complexity of the communication technique but is still a reliable option.

By increasing the number of receiving antennas to 8, as shown in Figure 3, translates in a positive impact in the performance results, because the level of diversity is duplicated. As will be viewed in the following, the MRC and EGC perform good with a number of receiving antennas, at least, four times higher than the number of transmitting antennas.

As can be seen from Figure 3, comparing the MRC against the EGC, the better performance results tend to be achieved by the MRC (for the same number of iterations). The best overall performance is achieved by the MRC, with 4 iterations of the interference cancellation, whose performance is very close to the MFB, and better than the ZF. It is worth noting that the ZF, implemented at the receiver side, suffers from noise enhancement, and therefore, its performance tends to be limited. It can also be noted that the MRC with $L = 4$ iterations corresponds to a significant improvement, as compared to the results obtained in the MIMO scenario of Figure 2, due to the higher diversity gain.

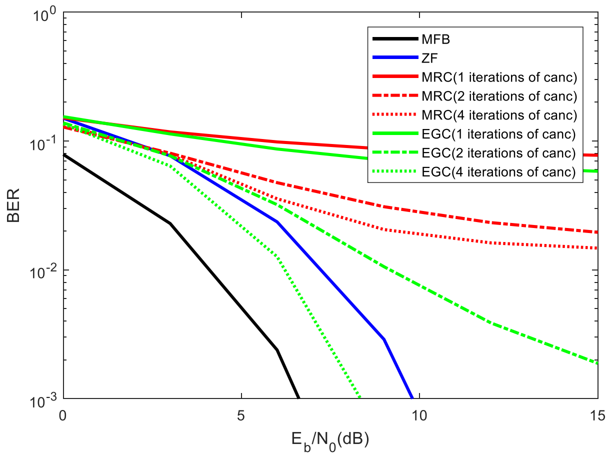

Figure 2: BER results with 2 transmitting antennas and 4 receiving antennas ($T = 2$, $R = 4$) in a MIMO scheme.

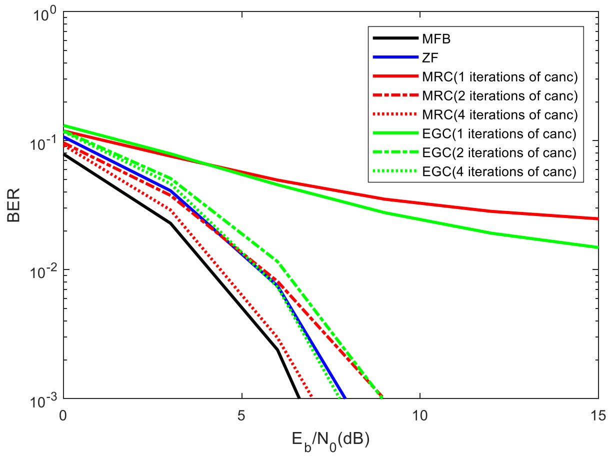

Figure 3: BER results using 8 transmission antennas and 2 receiving antennas ($T = 2$, $R = 8$), using a MIMO scheme.

It can also be noted that the degradation of performance obtained with the MRC and with the EGC with 2 iterations, as compared to 4 iterations, is not great. Therefore, if processing is a key issue, one can choose 2 iterations, instead of 4.

Figure 4 performs a comparison, for different receivers, between 4×16 MIMO with 8×32 MIMO. It is noticeable that the results with these two different MIMO diversities are insignificant. In fact, increasing the number of transmitting antennas corresponds to an increase of the symbols rate, which tends to degrade the performance (due to higher interference). On the other hand, an increase of the number of receiving antennas corresponds to an increase of diversity. Comparing 4×16 MIMO with 8×32 MIMO, we duplicate the transmitting and the receiving antennas, and therefore, the increase of diversity (receiving antennas) compensates the increase of symbols rate (transmitting antennas). Note that the number of receiving antennas is always four times higher than the number of transmitting antennas. As previously described, this is the rule for the MRC/EGC to perform well.

From Figure 4, it is noticeable that the best overall performance is achieved by the MRC, whose results are close to the MFB.

Figure 5 shows the results for 2×8 MIMO system, with different levels of correlation between transmitting and between different receiving antennas. In all cases, we used four iterations of interference cancellation. In case be seen that, without correlation, the performance obtained with the MRC is very close to the MFB. Nevertheless, as the level of correlation increases the performance degrades. A correlation between transmitting and between receiving antennas of 0.3 achieves a performance very close to the scenario without correlation. Nevertheless, when we increase the correlation to 0.5, we experience a high degradation of performance, which is even worse for correlation 0.8. It is also shown that the performance obtained with the MRC and correlation 0.3 is still better than that obtained with the ZF without correlation, due to the noise enhancement of ZF. As before, it is also noticeable that the MRC performs better than the EGC, for all levels of correlation. Then only case where the EGC performs better than the MRC is the situation where the number of receiving antennas is less than four times higher than the number of transmitting antennas.

From Figure 5 is can also be viewed that the degradation of performance with the increase of correlation is higher for the MRC than for the EGC. In fact, for correlation 0.8, the results obtained with the EGC are not so weak as those obtained with the MRC. Therefore, it can be concluded that the EGC is more resistant to correlations than the MRC, but the latter achieves better performances for low levels of correlation.

This analysis of performance as a function of the correlation is important because with the available technology, in the underwater environment, it is still not possible to create a system with multiple antennas that are spaced enough to be uncorrelated. Such system would end up being gigantic, and so the system implemented in a real world should remain some degree of correlation. Fortunately, the performance obtained with low levels of correlated MRC is almost the same as the non-correlated MRC.

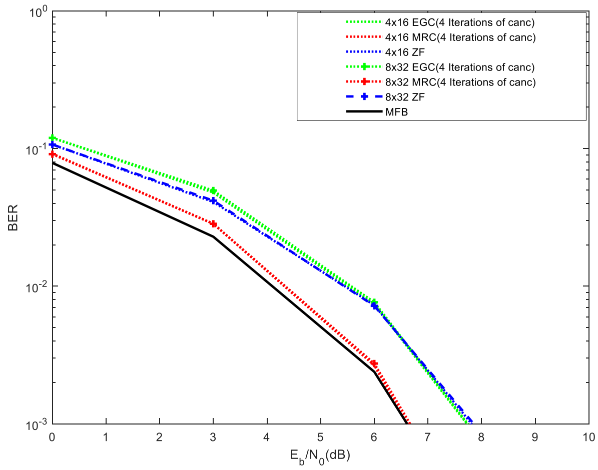

Figure 4: BER results for different MIMO configurations.

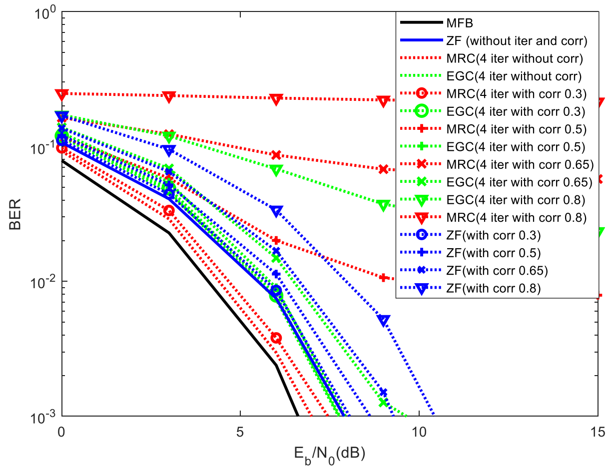

Figure 5: Results for 2×8 MIMO system, with different levels of correlation.

5. CONCLUSIONS

In such an adverse environment, like the UWA, it was shown that it is still possible to create a MIMO communication system than mitigates the impairments and supports higher throughputs.

It was viewed that the performance of the ZF, implemented at the receiver side presents noise enhancement, and therefore, the results are always limited. Moreover, it was described that a disadvantage of the ZF algorithm relies on the need to compute the pseudo-inverse of the channel matrix, for each frequency component. To avoid this and simplify this process, we have considered the use of the MRC and EGC. A disadvantage of these algorithms relies on a certain level of interference that is generated. To remove this interference, we have proposed an iterative interference canceller, as being part of the proposed receiver. It was also shown that the performance obtained with the MRC, with correlation of 0.3, is very close to that obtained with the MRC without correlation, and still better than that of ZF. The MRC tends to achieve better performance than the EGC, for zero or low levels of correlation. On the other hand, for high levels of correlation, the EGC does not achieve a performance so poor as the MRC.

Implementing the MRC and EGC algorithms for m-MIMO, we avoid the computation of the pseudo-inverse matrix, and therefore simplify the processing, while achieving a performance very close to the MFB, especially with 4 iterations of the interference canceller, even in an adverse environment, such as UWA.

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