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LINEAR MULTIUSER DETECTION IN FLAT RAYLEIGH FADING CHANNELS

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This paper presents the results obtained by two linear multiuser detectors, namely the decorrelating detector and the minimum mean square error (MMSE) one, when the channel is affected by the flat Rayleigh fading and gray images are transmitted through the system. All the users transmit their information with the same power, but the spreading codes are correlated one another. We will investigate the fading effect on the received images and the impact of the cross-correlation of the spreading codes on the quality of the received images. In the end, several conclusions are highlighted, with respect to the level of performance achieved.

Keywords: decorrelating detector, MMSE detector, space–time block coding, universal image quality index, multi-scale structural similarity index, visual information fidelity index

1. Introduction

The purpose of linear multiuser detection (MUD) is to get close to the capacity of the optimum MUD with a reasonable implementation complexity. This class of detectors is designed to reduce the multiple-access interference (MAI) according to a specific criterion [1]. There are two important types of linear MUD, namely decorrelating detector and MMSE detector. The first has the role to completely eliminate the MAI for all users, while the MMSE one tries to minimize the square of residual noise plus interference [1, 2]. The MAI reduces the performance of the detectors as the number of the users is increasing and the near-far effect is present. Another phenomenon that degrades the performance of MUD detectors is the fading, which appears in most wireless communication systems, especially when high data rates are implied [3, 4].

The bit-error rate (*BER*) performance of the MUD in additive white Gaussian noise (AWGN) channels has been heavily studied and over the years a lot of multiuser detectors have been proposed [5]. Recent studies have shown that combining DS-CDMA systems with Multiple Input Multiple Output (MIMO)

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techniques can increase the performance of the MUD. This is realized by exploiting the spatial diversity, by using multiple antennas at the transmitter and the receiver [6, 7]. MIMO-CDMA systems are also more robust to multiple access interference than single input single output (SISO) DS-CDMA systems [8].

The purpose of this paper is to analyze the performance of the abovementioned linear multiuser detectors, when the channel is affected by the flat Rayleigh fading in DS-CDMA system in two configurations: SISO channel and when Alamouti's space time block codes (STBC) is used. In order to take account of the human perception, we chose to use gray-type images instead of random bits and to use some other metrics beside the classical *BER* to evaluate the performance.

The paper is organized as follows. In section 2 is provided a brief description of the linear multiuser detectors and of the implementation of the STBC technique used, while in section 3 is provided a short explanation of the specific metrics used to compare the recovered images with the original ones. In section 4 are presented the simulation methodology and the results obtained, based on the simulation. The final section concludes this paper.

2. System model

It is known that in a CDMA system with N users, in which all users employ synchronous binary phase-shift keying (BPSK) modulation, through a channel affected by the flat fading, the received signal is given by [9]:

$$y(t)=\sum_{k=1}^{N}|A_k|e^{j\theta_k}b_k s_k(t)+n(t),\ldots t\in[0,T], \tag{1}$$

where $A_k=|A_k|e^{j\theta_k}$ is the received amplitude of the k user, $b_k\in\{\pm1\}$ is the information transmitted by the k user, $s_k(t)$ is the signature of the k user and $n(t)$ is the AWGN with unit power spectral density.

The linear multiuser detectors involve a linear transformation to the matched filter outputs. The decorrelating detector applies the inverse of the correlation matrix, $\mathbf{R}$, in order to decouple the data [2]. In the flat fading channel the receiver must know also, beside $\mathbf{R}$, the incoming phases of the users [9]:

$$\hat{b}_k=\operatorname{sgn}(\operatorname{Re}\{(\mathbf{R}^{-1}\mathbf{y})_k e^{-j\theta_k}\}). \tag{2}$$

This detector completely eliminates the MAI, hence is near-far resistant, but the main disadvantage of this detector is that it enhances the noise [2].

The MMSE detector implements a linear mapping which minimises the mean square error between its outputs and the transmitted data [10]. This detector performs better than the decorrelating one, since it takes also the noise into account, but the main disadvantage is the need of estimating the channel at the receiver [2]. The detection scheme can be written as [11]:

$$\hat{\mathbf{b}} = \mathrm{sgn}(\mathrm{Re}\{\mathbf{A}^{*}(\mathbf{R} + \sigma^{2}\mathbf{A}^{-2})^{-1}\mathbf{y}) . \quad (3)$$

A solution to improve the performance of the linear MUD in presence of flat fading is the use of spatial diversity [12]. In this paper we will focus on spatial diversity, specifically in Alamouti's space time block codes (STBC), where users have two transmit antennas and at the receiver there is only one antenna (MISO channel). A simplified block diagram of the transmitter used in our simulations is shown in Fig. 1.

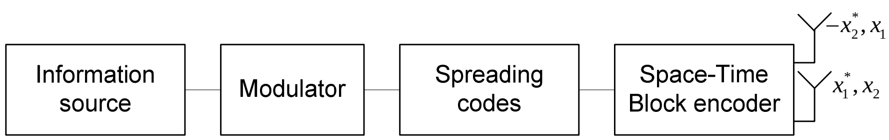


Fig. 1 The block diagram of the transmitter

In the case of Alamouti code, described by Eq. (4), the data x_1 and $-x_2^*$ are transmitted from the first antenna, while x_2 and x_1^* from the second one, where * denotes complex conjugation [13].

$$\mathbf{X} = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix} \quad (4)$$

Assuming that the channel is affected by flat fading and $\mathbf{h} = [h_1, h_2]^T$ describes the complex channel matrix, the received matrix, $\mathbf{y}$, which contains information from two consecutive received data samples, is [13]:

$$\mathbf{y} = \mathbf{X}\mathbf{h} + \mathbf{n} . \quad (5)$$

More explicitly Eq. (5) can be written as:

$$y_1 = h_1 x_1 + h_2 x_2 + n_1,$$
$$y_2 = -h_1 x_2^* + h_2 x_1^* + n_2, \tag{6}$$

which leads, after simple mathematical manipulation, to [13]:

$$\hat{x}_1 = h_1^* r_1 + h_2 y_2^*$$
$$\hat{x}_2 = h_2^* r_1 - h_1 y_2^* \tag{7}$$

3. Performance metrics

When image transmission is involved, there are a lot of metrics that can be used to determine the quality of the recovered images and to determine the achieved performance of the involved system, beside the classical bit error rate (*BER*). The metrics used in this paper to compare the recovered images with the original ones are based on the Human Visual System (HVS), because metrics like mean squared error (*MSE*) and peak signal to noise ratio (*PSNR*) does not offer such a good measure of visual quality [14]. The following metrics were chosen: universal image quality index (*UQI*), multi-scale structural similarity index (*MS-SSIM*) and visual information fidelity index (*VIF*).

The Universal Image Quality Index takes in consideration three factors: loss of correlation, luminance distortion and contrast distortion [15]. The multi-scale structural similarity index is based on the *SSIM* index and in the same time takes into account the fact that images are multi-scale and the HVS processes visual information at multiple resolutions. Therefore the image quality is evaluated at multiple resolutions [16] and the final value is a combination of these evaluations [17]. The visual information fidelity index is based on information theory and is giving very accurate image similarity values, but at the cost of very high computational complexity because it joins statistical models of all the components involved in the communication system [18].

All these three metrics in general take values between 0 and 1, where 0 indicates that all information about the original image has been lost (the receiver was unable to recover the reference image) and 1 is obtained when the receiver was able to realize a perfect recovery of the transmitted image. We used the term “in general” because *VIF* has a particularity: it is possible to obtain an enhancement of the contrast of the original image (so the perceptual quality increases) and therefore the *VIF* value becomes larger than unity [18].

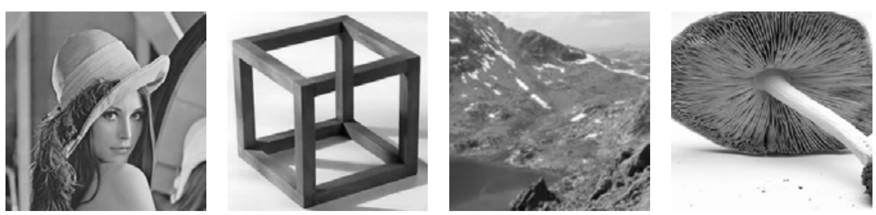
All the obtained results, regarding the values achieved by the metrics, were possible using the software from [19].

4. Simulation results

In this section are presented the results obtained by the two linear detectors, when four users are transmitting gray image data. The codes used to separate the users are not orthogonal, with the inter-correlation matrix:

$$\mathbf{R} = \begin{bmatrix} 1 & -0.5 & 0.25 & 0.25 \\ -0.5 & 1 & 0.25 & 0.25 \\ 0.25 & 0.25 & 1 & 0 \\ 0.25 & 0.25 & 0 & 1 \end{bmatrix}, \qquad (8)$$

and the data are transmitted with the same power. In each of the cases described in Section 2, the four users transmit their own image (Fig. 2) over a channel affected by flat Rayleigh fading. At the receiver the recovered images are compared with the original one, using the metrics presented in the previous section, with the scope of establishing which detector achieves better performance. The decorrelating detector and the MMSE one are compared in two scenarios. In the first one, each user has one antenna at both the transmitter and the receiver end (this case is noted further as SISO channel). In the second scenario, the users have at their disposal two antennas at the transmitter and one at the receiver (noted further as MISO channel).



a) Image used by first user **b) Image used by second user** **c) Image used by 3th user** **d) Image used by 4th user**

Fig. 2 Images transmitted by the users

In Fig. 3 are presented the results obtained by the decorrelating detector (Fig. 3.a) and by the MMSE detector (Fig. 3.b), when the channel is affected by the fading and AWGN (continuous curves) and by the AWGN only (dashed curves). As it can be seen in Fig. 3.a, the decorrelating detector is not able to recover the transmitted data when the fading is present on the channel, not even for high signal to noise ratio (*SNR*). It can be easily concluded that the channel fading deteriorates completely the detector performance. For the AWGN only case, the increase of *SNR* leads to a decrease in BER, but, for the Rayleigh fading case, the *BER* is almost constant for all *SNR*'s, having a slight variation around $10^{-0.3}$ for all the users.

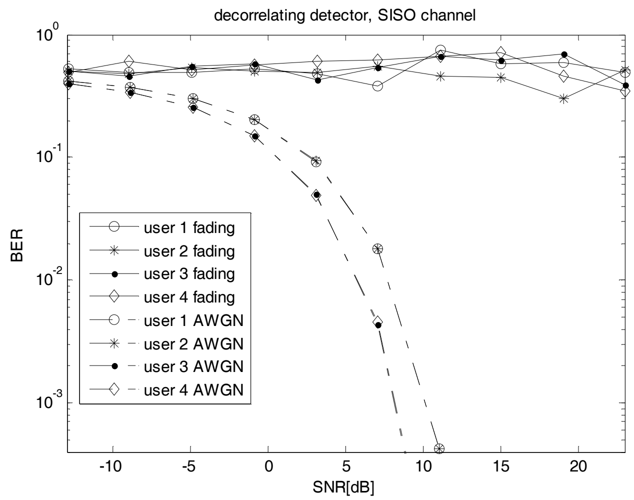


Fig. 3.a *BER* vs. *SNR*, decorrelating detector, SISO channel affected by flat Rayleigh fading and AWGN.

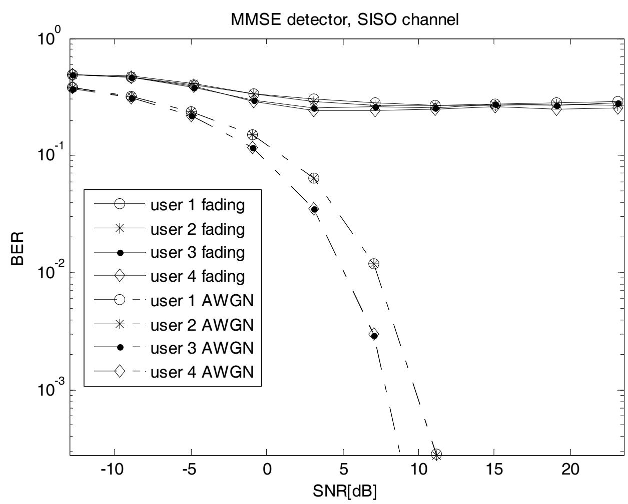
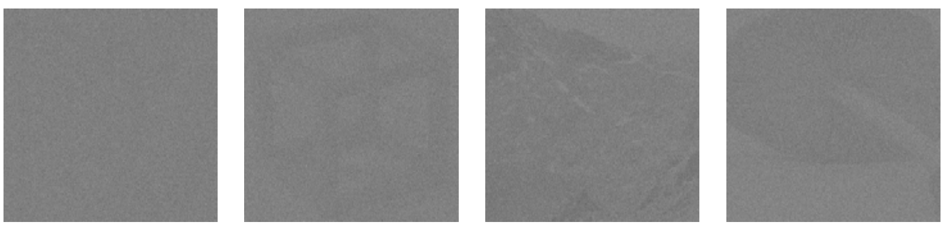


Fig. 3.b *BER* vs. *SNR*, MMSE detector, SISO channel affected by flat Rayleigh fading and by AWGN.

In the case of MMSE detector, we can see a slight decrease of *BER* with *SNR* in the presence of fading, from $10^{-0.3}$ to $10^{-0.6}$, but the values of *BER* are still high for large values of signal to noise ratio. From the point of view of the bit error rate results, we can conclude that, when the users are inter-correlated and in the presence of Rayleigh fading, both detectors are failing to recover the transmitted data.

To be sure of the values obtained by the metrics, the mean of M recovered images was determined for each user. Calculating the mean of M recovered images, an increase of *SNR* is obtained, due to the noise mediation, with $20\lg\sqrt{M}$.

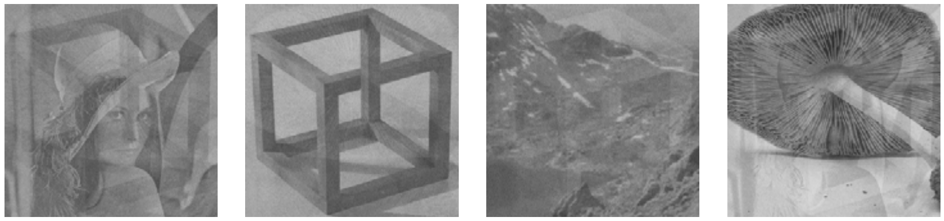
In Fig. 4 (a- decorrelating detector, b- MMSE detector) are presented the images resulted after the mediation of 100 images with a *SNR* equal to 1.1 dB. In the case of decorrelating detector, the recovered images are unrecognizable, and, therefore, all the metrics used to determine the quality of the images have values very close to zero, so it is very easy to note that the flat Rayleigh fading is completely deteriorating the recovering process.



user 1	user 2	user 3	user 4
MS-SSIM=0.086	*MS-SSIM=0.123*	*MS-SSIM=0.345*	*MS-SSIM=0.256*
VIF=0.004	*VIF=0.032*	*VIF=0.061*	*VIF=0.035*
UQI=0.001	*UQI=0.023*	*UQI=0.09*	*UQI=0.056*

Fig. 4.a The recovered images by decorrelating detector, *SNR* equal with 1.1+20 dB

In the case of MMSE detector, the analysis of the recovered images shows that the MMSE detector is partially able to recover the transmitted images (Fig. 4b) and that the effect of inter-correlation between codes is reflected in all the recovered images. Every image estimated by the detector contains information from the other images. If we take into account the correlation matrix, we are expecting that the images recovered by the 3rd and the 4th user to have a better quality than the images recovered by the other users. This fact is sustained by the multi-scale structural similarity index (*MS-SSIM*) and universal image quality index (*UQI*), the values obtained by them are with almost 0.2 higher for the 3rd and 4th users. If we analyze the quality of the recovered images regarding the visual information fidelity index (*VIF*) we can observe that the images have approximately the same quality, fact which is sustained by the human eye perception and is not reflected by the *BER* results.



user 1	user 2	user 3	user 4
MS-SSIM=0.591	*MS-SSIM=0.685*	*MS-SSIM=0.723*	*MS-SSIM=0.778*
VIF=0.223	*VIF=0.345*	*VIF=0.307*	*VIF=0.392*
UQI=0.351	*UQI=0.381*	*UQI=0.5*	*UQI=0.611*

Fig. 4.b The recovered images by MMSE detector, *SNR* equal with 1.1+20 dB

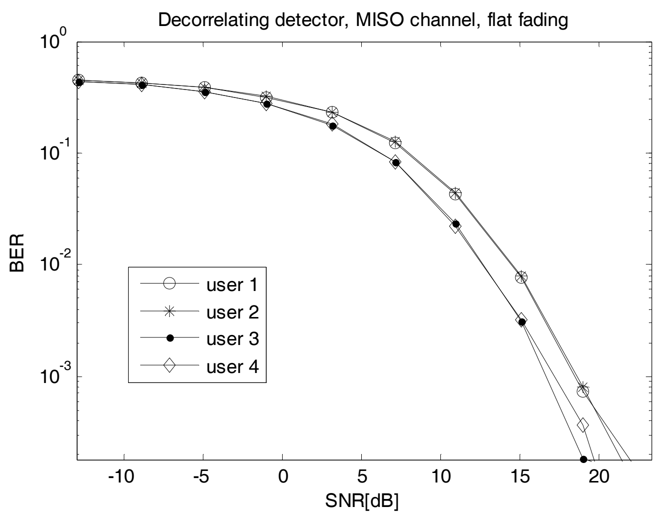


Fig. 5.a BER vs. SNR, decorrelating detector, MISO channel affected by flat Rayleigh fading.

As we mentioned, a solution to improve the performance of the multiuser detectors is to use spatial diversity, more exactly space time block codes. In Fig. 5.a and 5.b we can observe the results of bit error rate obtained by the detectors depending on *SNR*. We can observe that there is a significant improvement with respect to the previous case, since the *BER* decreases to less than 10^{-4} as *SNR* grows to 30 dB. Moreover the curves point out also the correlation between the users. The best results are obtained by the 3rd and 4th users, which, according to the correlation matrix, are the least correlated. Further, the two graphs are approximately identical. So, using the *BER* metrics, we do not observe any difference between the performances of these detectors. This observation is not valid if we compare the recovered images, Fig. 6.a, 6.b, 6.c, 6.d.

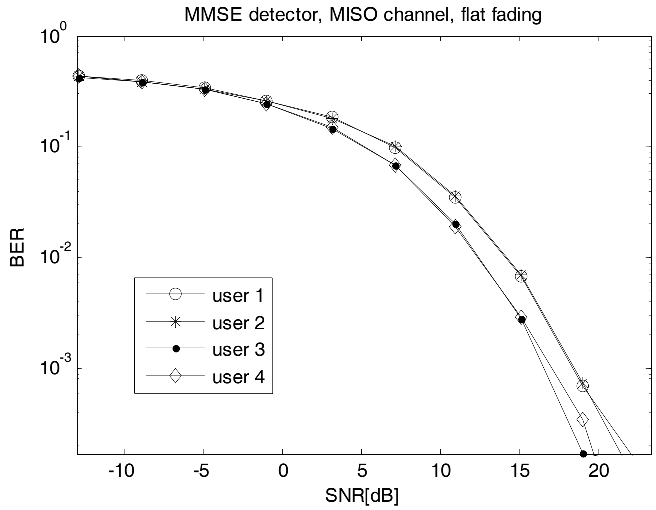
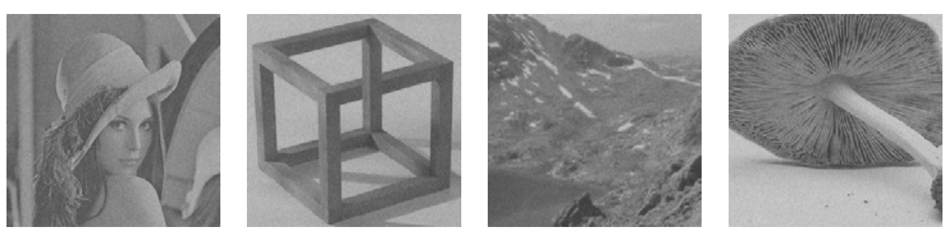


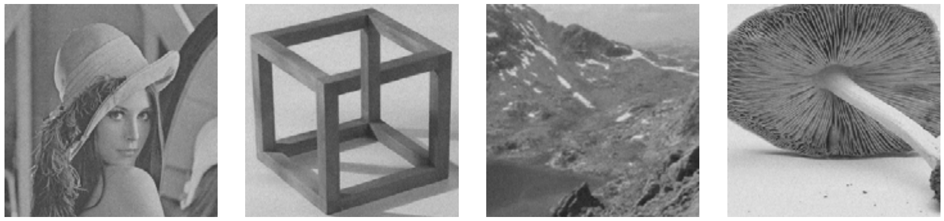
Fig. 5.b *BER* vs. *SNR*, MMSE detector, MISO channel affected by flat Rayleigh fading.

If we analyse the images from Fig. 6.a (decorrelating detector) and 6.c (MMSE detector), obtained for the same *SNR*, equal to 21.1 dB (including the mediation of the noise), we can observe that the values obtained by the metrics are similar, so, from their point of view, the quality of the recovered images is the same. This fact is no sustained by the human eye perception. For example, in the image estimated by the MMSE detector for the first user we can observe pieces of information from the images recovered for the second and 4th users. The same thing is happening, also, for the rest of users. This affirmation is not valid for the images recovered by the decorrelating detector, but these images are darker.



user 1	user 2	user 3	user 4
MS-SSIM=0.765	*MS-SSIM=0.756*	*MS-SSIM=0.848*	*MS-SSIM=0.847*
VIF=0.364	*VIF=0.409*	*VIF=0.427*	*VIF=0.452*
UQI=0.473	*UQI=0.412*	*UQI=0.581*	*UQI=0.610*

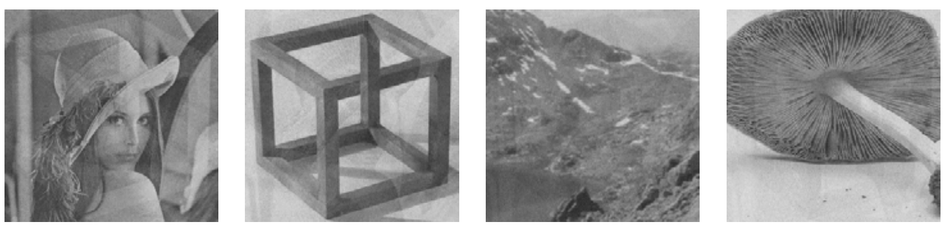
Fig. 6.a The recovered images by decorrelating detector, MISO channel, *SNR* equal with 21.1 dB



user 1	user 2	user 3	user 4
MS-SSIM=0.905	*MS-SSIM=0.903*	*MS-SSIM=0.951*	*MS-SSIM=0.951*
VIF=0.521	*VIF=0.561*	*VIF=0.611*	*VIF=0.630*
UQI=0.640	*UQI=0.556*	*UQI=0.739*	*UQI=0.746*

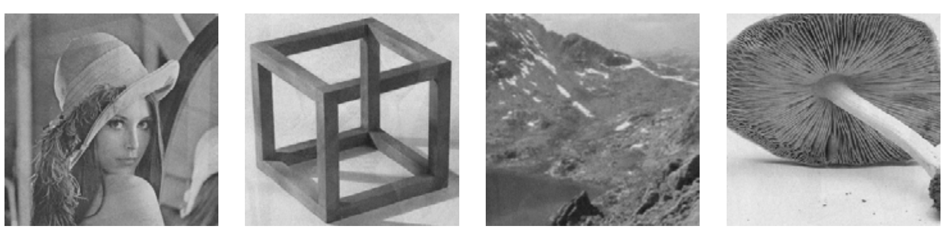
Fig. 6.b The recovered images by decorrelating detector, MISO channel, *SNR* equal with 25.1 dB

If the *SNR* is higher, equal with 25.1 dB (Fig. 6.b and 6.d), we can observe an improvement in the quality of the recovered images. The values of the metrics are increasing with almost 0.15, but this growth is not large enough to say that the images are a good representation of the original ones. The images are lighter for both detectors, but still the images estimated by the MMSE detector hold extra information, for example: the Fig. 6.d in which the image of the first user contains data from the second user.



user 1	user 2	user 3	user 4
MS-SSIM=0.765	*MS-SSIM=0.756*	*MS-SSIM=0.848*	*MS-SSIM=0.847*
VIF=0.364	*VIF=0.409*	*VIF=0.427*	*VIF=0.452*
UQI=0.473	*UQI=0.412*	*UQI=0.581*	*UQI=0.611*

Fig. 6.c The recovered images by MMSE detector, MISO channel, *SNR* equal with 21.1 dB



user 1	user 2	user 3	user 4
MS-SSIM=0.919	*MS-SSIM=0.932*	*MS-SSIM=0.956*	*MS-SSIM=0.957*
VIF=0.502	*VIF=0.550*	*VIF=0.605*	*VIF=0.629*
UQI=0.682	*UQI=0.597*	*UQI=0.768*	*UQI=0.767*

Fig. 6.d The recovered images by MMSE detector, MISO channel, *SNR* equal with 25.1 dB

5. Conclusions

The purpose of this work was to compare the performance of two linear detectors, when the channel is affected by Rayleigh flat fading. In the SISO case, based on the point of view of the *BER* metric, both decorrelating and MMSE detectors are getting very poor results; however, the multi-scale structural similarity index shows that the MMSE receiver is able to recover approximately 50% from the original image, based on the image self-redundancy. In the case of MISO channel, the performance is disputable. If we take into account only the results obtained by the bit error rate and by the metrics, the performance for both detectors are very close, but the human eye perception does not agree. The images recovered by the decorrelating detector do not contain extra information (information from the other images), but are darker. In the case of MMSE detector the observations are opposite: lighter images, but with extra information. Overall, even if the SNR is 21.1 dB or with 5 dB higher, the images are blurred for both detectors.

In conclusion, the space time block codes bring an important improvement in the performance of both decorrelating and MMSE detectors, but are not able to eliminate completely the fading and noise effects. We have to emphasize that no filtering or image processing have been applied. The images have been used only for the purpose of creating a picture closer to human perception for the detectors analysed. For further work, we propose to include also the case of other types of fading, such as Rice, Nakagami-m and lognormal fading.

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