OFDM/CDMA channel quality estimation using K-means algorithm

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ABSTRACT

This work aims to estimate the transmission channel quality and suggest a possible way to enhance the data rates to satisfy the increasing demand for higher data rates to a certain extent. The combination of any non-orthogonal subcarrier multiplexed (SCM) with CDMA needs a large bandwidth, hence a limited number of subcarriers and number of users as well as lower data rates. In contrast, orthogonal subcarriers such as the case of OFDM which are closely spaced due to their orthogonality property as well as to their reduced frequency selectivity fading are, therefore, crucial for increasing subcarriers and thus, increasing the data rates as well as the number of users. To describe the OFDM/CDMA technique in more detail, we performed a simulation using the software Scilab 5.5.2. In this simulation, we treat a simple example of a certain number of users using a bipolar orthogonal code, particularly, the Hadamard/Welsh code for the OCDMA, and the fast fourier transform (FFT) algorithm for the OFDM. For a more realistic simulation, we have introduced a gaussian white noise in the transmission channel and studied the effect of this noise on the eye diagram. Finally, to avoid the computational complexity in calculating the BER to study the OFDM/CDMA channel system quality, we have instead computed the bias and the variance of a noisy 16- quadrature amplitude modulation (QAM) constellation at the reception using the K-means algorithm.

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1. INTRODUCTION

With the increased demand for higher data rates, there is a need for accurate and rapid transmission of information. To satisfy this huge demand, diverse technologies have been proposed for higher data rate transmission. Among these technologies, frequency division multiplexing (FDM) transmits multiple signals simultaneously through the same channel in which a specific frequency band is assigned to each signal [1], [2]. However, the most inconvenient drawback is that the frequency band overlapping is not tolerated, and hence the number of users is limited. To overcome this problem and increase the number of users /or the data rate, OFDM [3], [4] which is a certain desired number of multicarriers that are orthogonal to each other, is largely used due to its spectral efficiency superiority over the FDM. OFDM is used mainly in communications networks due to its high-rate transmission ability with high bandwidth efficiency. The spectral efficiency of OFDM by tolerating the overlapping in the frequency domain and its robustness concerning multi-path fading of OFDM, are consequences of its orthogonality property. This property leads to the modulation of OFDM by an orthogonal matrix such as the discrete fourier transform (DFT) matrix which is computed using the FFT algorithm [5]. Since the DFT matrix is orthogonal then its inverse is equal to its transpose-conjugate which is the inverse discrete fourier transform (IDFT), and as a consequence, the information modulated by the IFFT is entirely recovered without interference by demodulating the received information at the reception using the FFT. CDMA, on the other hand, is based on orthogonal real codes matrix such as Hadamard matrix transformation. In this matrix, each line is a code assigned to a particular user. So, as the real codes matrix is orthogonal then its inverse is equal to its transpose, thus, although many different users can share the same frequency band channel simultaneously [6], each user's information is recovered entirely without interferences which means that only the intended receiver can decode the encoded information using the same code used by the corresponding transmitter. Many researchers have combined these two techniques OFDM and CDMA to enhance the data rates as well as to obtain better transmitted information accuracy. The latter does not, however, depend only on these techniques but the channel quality as well. Many channel quality estimation techniques were proposed in the literature [3]-[13]. In this work, we suggest a new channel quality estimation technique based on the K-means algorithm to determine the bias and the variance of the channel. The advantage of this technique is that it is simple and does not need too much complex computation. The combination of OFDM with CDMA, widely discussed in the literature [14], [15], has a great potential to enhance the data rate as well as the user number as it will be described step by step in the following.

2. OFDM/CDMA BLOCK DIAGRAM DESCRIPTION

A simple block diagram description is illustrated in Figure 1. First, the different user's digital information is gathered in one information data stream, and 16- quadrature amplitude modulation (QAM) modulated. The Hadamard/Welsh code matrix is then applied to this QAM modulated information in order to assign each matrix line, representing a code, to each user. To increase the data rate, the IDFT algorithm is applied to the resulting encoded information using the FFT algorithm and followed by inserting a cyclic prefix (CP) [16], [17] to prevent inter-symbol interferences. The IDFT signal will be converted to an optical signal and transmitted via an optical channel.

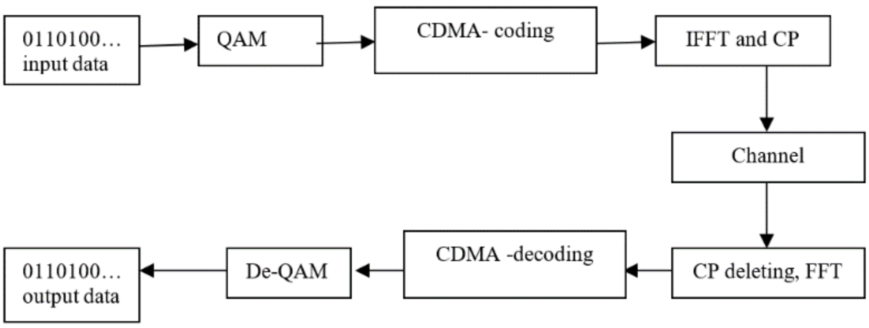


Figure 1. Block diagram of CDMA/OFDM transmission

At the reception, the optical signal is reconverted back to the electrical signal, and after removing the CP, the DFT is applied to transform the information back to fourier space. Later, each user can extract the intended QAM information using the assigned code. Finally, the transmitted digital information is recovered back after QAM demodulation.

2.1. Transmission

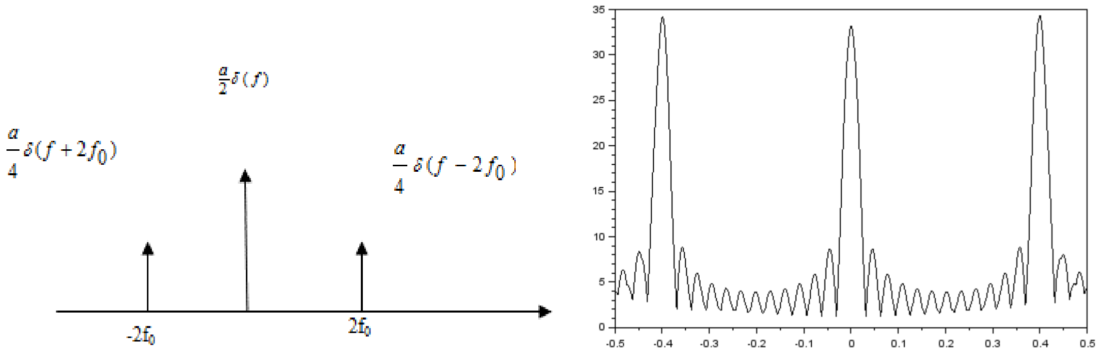
Since this work aims to estimate the channel quality and to discuss how data rates can be increased, then QAM is another technique usually combined with OFDM to increase the data rate. So, instead of just one byte per unit of time, we get four bytes when using QAM-16 [18], and hence the rate is increased four times. The basic concept of QAM is to use cosine as in-phase and sinus as in quadrature for the QAM base vectors [19]. So, a given constellation point with coordinates *a* and *b* can be represented by the following QAM modulation vector at the transmission.

$$S(t) = a\cos(2\pi f_0 t) + b sin\,(2\pi f_0 t) \tag{1}$$

The QAM demodulation at the reception corresponds to the extraction of these two coordinates. For example, to extract the coordinate a, we multiply this vector by the in-phase base vector $\cos(2\pi f_0 t)$ at the reception and then apply the fourier transform whose real part is given as:

$$X(f) = Re\,(TF[S(t).\cos(2\pi f_0 t)]) = \frac{a}{4}[\delta(f - 2f_0) + \delta(f + 2f_0)] + \frac{a}{2}\delta(f) \tag{2}$$

Where $\delta(f)$ is the Dirac distribution, TF is the Fourier transform, and f_0 is the alternating voltage frequency. The graph of this analog expression and its corresponding numerical version are illustrated in Figure 2, where Figure 2(a) represents the real part Fourier transform $X(f)$ and Figure 2(b) shows its corresponding discrete-time Fourier transform magnitude.



(a) (b)

Figure 2. The graph of (a) real part fourier transform $X(f)$ and (b) its corresponding discrete time fourier transform magnitude

The central peak corresponds to the first FFT value of $a\cos^2(2\pi f_0 t)$ in practice (FFT (0)).

$$\frac{a}{2}\delta(f) = \frac{a}{2}TF(1) \approx \frac{a}{2}TF\left[Re\;ct_{L_b}(n)\right] = \frac{a}{2}\frac{\sin(\pi L_b f)}{\sin(\pi f)} \tag{3}$$

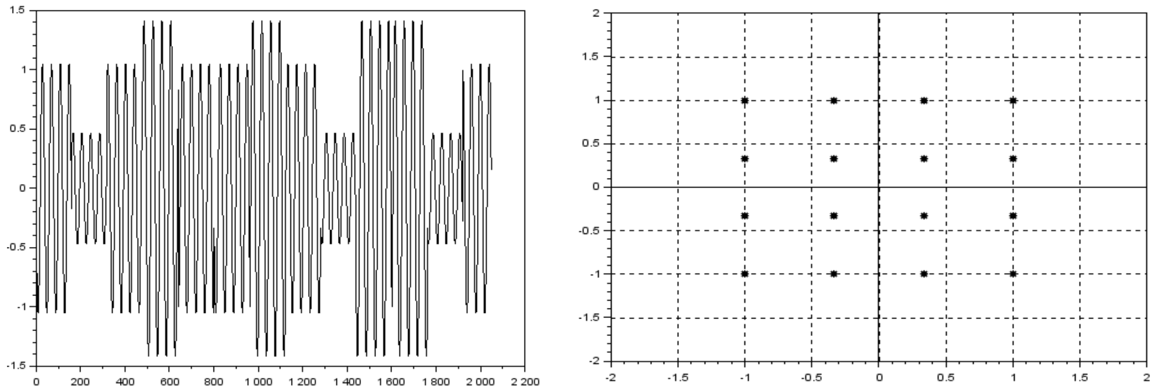
So, the first FFT value of $a\cos^2(2\pi f_0 t)$ is obtained when f goes to '0' hence the received digital value a is given by:

$$\begin{cases} a = 2 \times \frac{FFT[a\cos^2(2\pi f_0 t)]}{L_b} \\ \qquad f \to 0 \end{cases} \tag{4}$$

L_b is the binary symbol duration. In practice, each couple (a, b) of the QAM-16 constellation is obtained using a narrow low-pass filter and then converted it to its corresponding quadruple number of bytes to reconstruct the transmitted digital information at the reception, as shown in Figure 3.

Figure 3(a) shows an example of a transmitted QAM-16 signal, and Figure 3(b) shows the corresponding constellation obtained at the transmission using Scilab 5.5.2. The QAM signal shown in Figure 3 is encoded using orthogonal Hadamard/Welsh code. The resulting encoded information signal is shown in Figure 4. The use of orthogonal code matrices for encoding user information (CDMA) [20], such as the Hadamard matrix, is crucial for multiplexing as well as extracting the intended information by the intended receiver without other users interferences.

The encoded signal shown in Figure 4 is processed using the IDFT [21] to increase the data rates. The IDFT is efficiently implemented as an Inverse (IFFT). The resulting IFFT signal is then converted to an optical signal and transmitted through an optical waveguide. Figure 5 shows the IFFT signal in different channel conditions: Figure 5(a) displays the signal in a non-noisy channel, while Figure 5(b) displays it in four noisy channels with different standard deviations.



(a) (b)

Figure 3. Formation of QAM-16 symbols, where each (a, b) pair is shaped using a narrow low-pass filter and mapped to its corresponding digital representation (a) QAM-16 signal and (b) QAM-16 constellation at the transmission

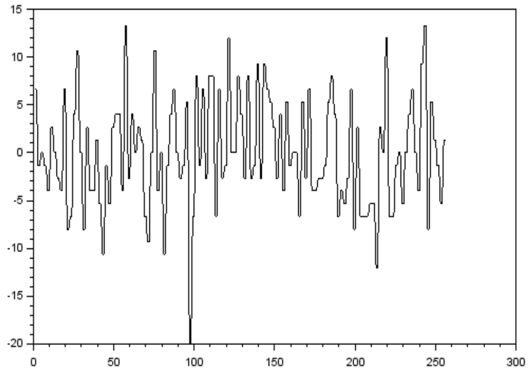
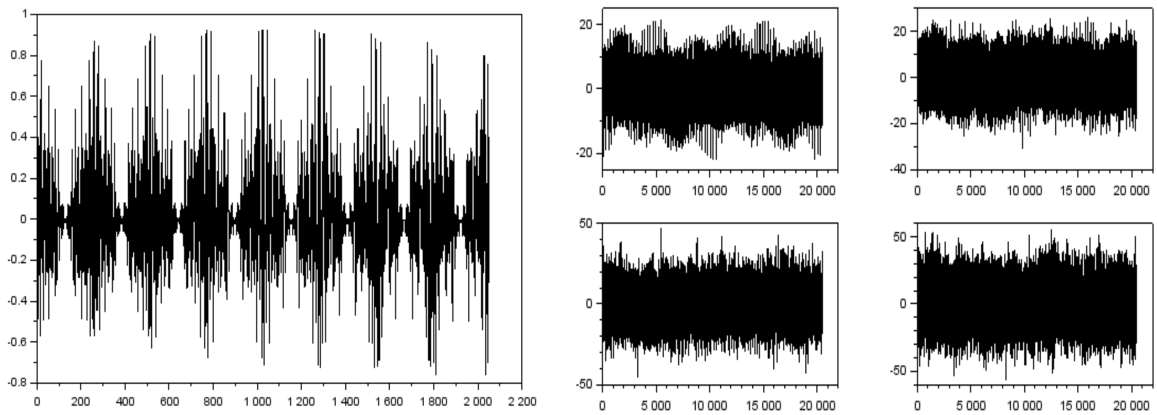


Figure 4. Encoded user information



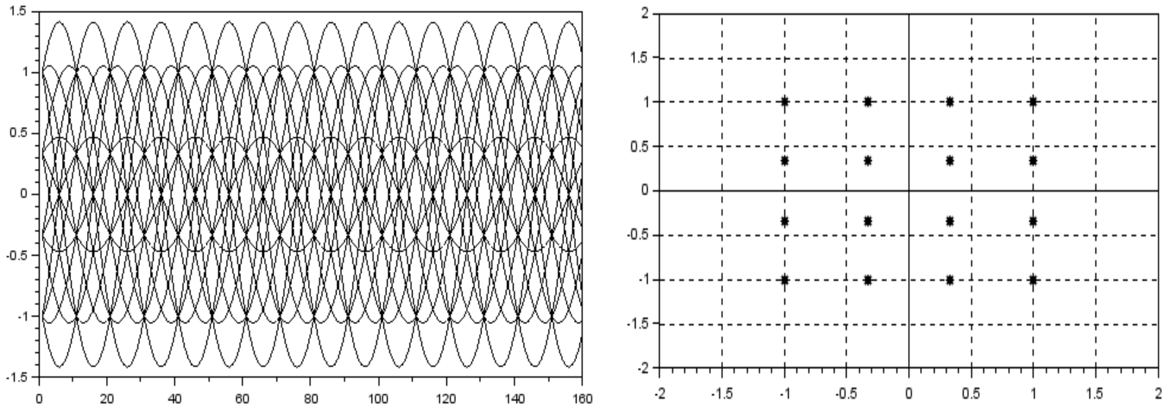
(a) (b)

Figure 5. IFFT signal in different channel conditions (a) non noisy IFFT signal and (b) IFFT noisy signal for 4 different wait noise std

2.2. Reception

Figure 6 exhibits the eye diagram and its corresponding 16-QAM constellation. For a non-noisy channel under ideal conditions, the resulting eye diagram [22] and the received constellation are shown in Figure 6(a) and Figure 6(b), respectively.

The eye diagram presented in this work illustrates the behavior of the QAM signal throughout the transmission channel. It can be observed that the "eyes" are widely open, indicating no significant noise or intersymbol interference. This is confirmed by the corresponding constellation diagram, where all the constellation points are located precisely at their ideal theoretical coordinates.



(a) (b)

Figure 6. Exhibits the eye diagram and its corresponding 16-QAM constellation (a) eye diagram-like for non-noisy channel ($std = 0$) and (b) corresponding QAM-16 constellation

2.3. Channel estimation quality using K-means algorithm

The QAM constellations are frequently affected by the orthogonal frequency division multiplexing (OFDM/CDMA) transmission channel noise [23]. In this work, we have simulated the latter as a gaussian-centered white noise (GCWN) [24]. The latter influence on the OFDM transmission is estimated by computing the bias and the variance of the noised QAM constellation at the reception using the K-means algorithm. So, as the noise standard deviation increases, the eyes of the diagram start getting narrower and the constellation points become wider as can be seen in Figures 7(a) and (b) to Figures 11(a) and (b) below. As it has been mentioned above, the estimation quality of a transmission channel can be well performed by computing its bias and standard deviation using the K-means algorithm [25]. The bias matrix is obtained by subtracting the constellation matrix at the transmission from the resulting constellation matrix obtained by the K-means. If Mt and Mr are the true constellation matrix at the transmission and the estimation constellation matrix at the reception, respectively, then the Bias matrix Mb is given as:

$$Mb = Mr - Mt = \begin{bmatrix} \hat{a}_{11} - a_{11} & \hat{a}_{12} - a_{12} & \hat{a}_{13} - a_{13} & \hat{a}_{14} - a_{14} \\ \hat{a}_{21} - a_{21} & \hat{a}_{22} - a_{22} & \hat{a}_{23} - a_{23} & \hat{a}_{24} - a_{24} \\ \hat{a}_{31} - a_{31} & \hat{a}_{32} - a_{32} & \hat{a}_{33} - a_{33} & \hat{a}_{34} - a_{34} \\ \hat{a}_{41} - a_{41} & \hat{a}_{42} - a_{42} & \hat{a}_{43} - a_{43} & \hat{a}_{44} - a_{44} \end{bmatrix} \quad (5)$$

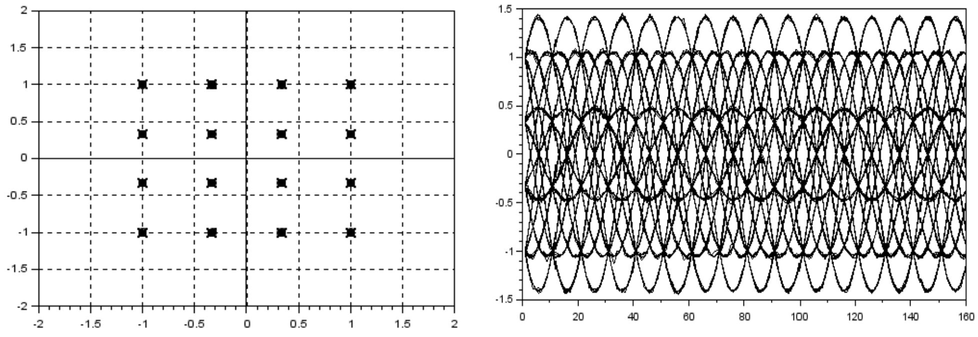
where $\hat{a}$ are the constellation referents values obtained by the K-means algorithm, and a are the true constellation values at the transmission. In addition, the standard deviation for each received constellation point *c*, where *k* is the number of the binary symbols in the concentration *c*, is given by the square root of the variance,

$$std_c = \sqrt{\frac{1}{k}\sum_{i=1}^{i=k}(a_{ci} - \hat{a}_c)^2} \quad (6)$$

a_{ci} represent the different received constellation values at the point c, and $\hat{a}_c$ is the corresponding estimated value obtained using the K-means. Similarly, a standard deviation matrix for the received constellation can be computed using (1).

$$std = \begin{bmatrix} std_{11} & std_{12} & std_{13} & std_{14} \\ std_{21} & std_{22} & std_{23} & std_{24} \\ std_{31} & std_{32} & std_{33} & std_{34} \\ std_{41} & std_{42} & std_{43} & std_{44} \end{bmatrix} \quad (7)$$

This method of evaluating these two matrices, allows us to identify which information binary symbol is more affected by the channel noise.



(a) (b)

Figure 7. The eye of diagram (a) like for noisy channel ($std = 0.01$) and (b) corresponding QAM-16 constellation
'*' K-means referents, 'o' received noisy QAM constellation and 'x' constellation at the transmission

3. RESULTS AND DISCUSSION

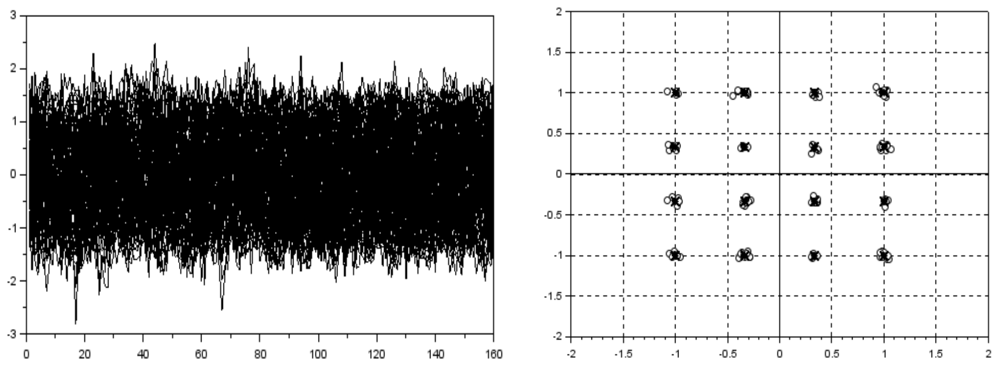
The following computed matrices Mb and Std are an example of the bias and the standard deviation (std), respectively, for a noisy channel (Figure 7) with $sdt = 0.01$. Each matrix element represents bias and std of a quadruple binary symbol. One can detect in these two matrices, the symbols that are more affected by a noisy channel.

$$Mb = \begin{bmatrix} 0.0005247 & 0.0009329 & 0.0005976 & 0.0010014 \\ 0.0016475 & 0.0010801 & 0.0007797 & 0.0016484 \\ 0.0005701 & 0.0006960 & 0.0020422 & 0.0005634 \\ 0.0010163 & 0.0003890 & 0.0007853 & 0.0018655 \end{bmatrix} \quad (8)$$

On the other hand, we can also compute the bias average $\langle Mb \rangle = 8.836 \times 10^{-4}$. The corresponding standard deviation std matrix is given by:

$$Std = \begin{bmatrix} 0.0050020 & 0.0057518 & 0.0049716 & 0.0049933 \\ 0.0049192 & 0.0051799 & 0.0052070 & 0.0053595 \\ 0.0050966 & 0.0049923 & 0.0049674 & 0.0048253 \\ 0.0045349 & 0.0043946 & 0.0044688 & 0.0045835 \end{bmatrix} \quad (9)$$

And its average is $mean\ (Std) = 4.9530 \times 10^{-3}$

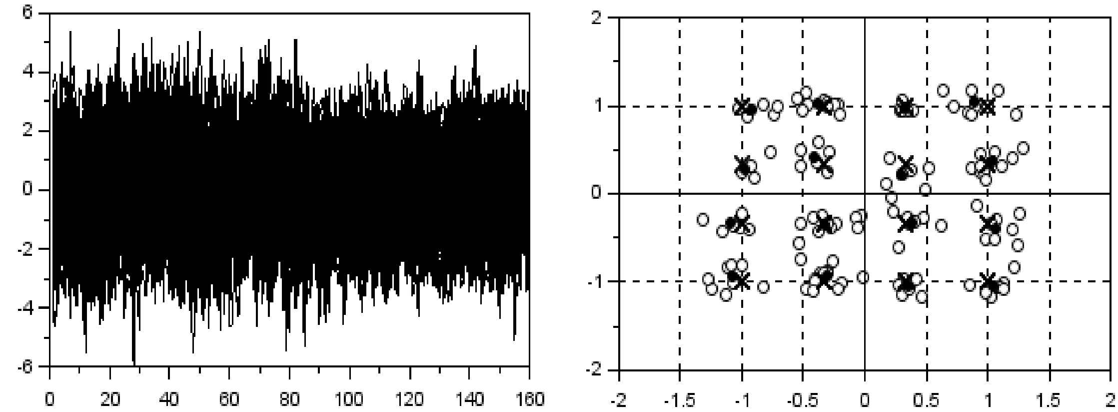


(a) (b)

Figure 8. The eye of diagram (a) like for noisy channel ($std = 0.2$) and (b) corresponding QAM-16 constellation '*'
K-means referents, 'o' received noisy QAM constellation and 'x' constellation at the transmission

As the noise standard deviation increases, the bias and standard deviation averages increase as observed in Figure 8 compared to Figure 7. The corresponding bias and standard deviation averages for the channel with noise $std = 0.2$, are mean $(Mb) = 1.92638 \times 10^{-2}$ and mean $(Std) = 3.61671 \times 10^{-2}$.

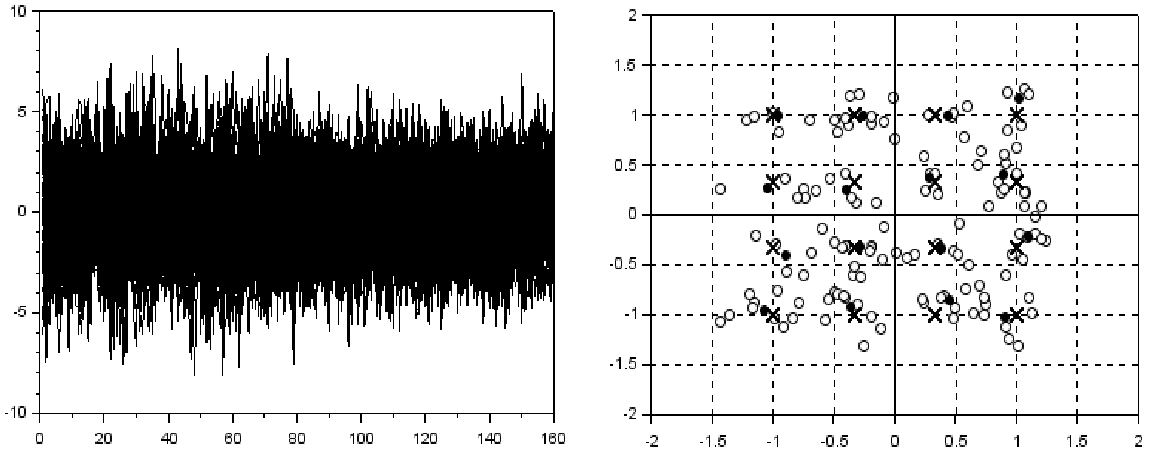
In the case of Figure 9 with channel noise $std = 0.2$, the bias and standard deviation averages, are $mean\ (Mb) = 7.30354 \times 10^{-2}$ and $mean\ (Std) = 11.40592 \times 10^{-2}$.



(a) (b)

Figure 9. The eye of diagram (a) like for a noisy channel ($std = 0.8$) and (b) corresponding QAM-16 constellation
'*' K-means referents, 'o' received noisy QAM constellation and 'x' constellation at the transmission

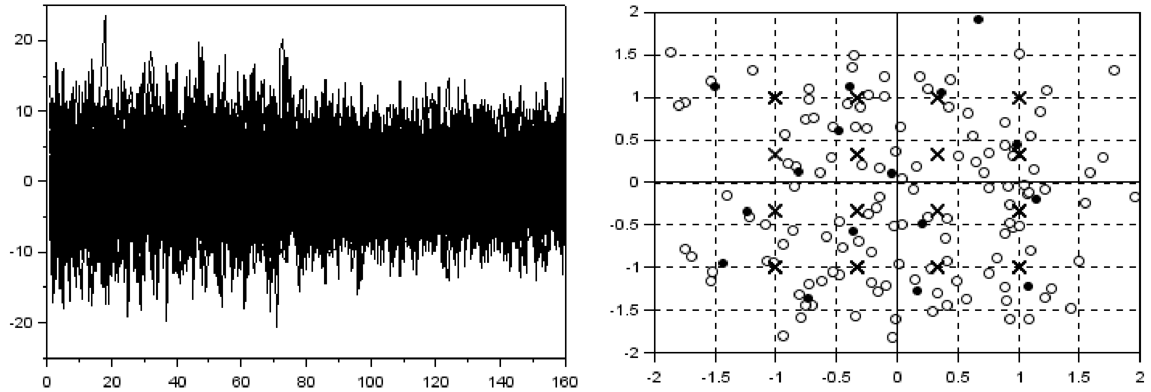
Figure 10 with channel noise $std = 1.2$, the bias and standard deviation averages, are $mean(Mb) = 9.96861 \times 10^{-2}$ and $mean\ (Std) = 18.02657 \times 10^{-2}$.



(a) (b)

Figure 10. The eye of diagram (a) like for a noisy channel ($std = 1.2$) and (b) corresponding QAM-16 constellation
'*' K-means referents, 'o' received noisy QAM constellation and 'x' constellation at the transmission

The channel with a noise $std = 3$, is illustrated in Figure 11. The bias and standard deviation averages, are mean $(Mb) = 36.21774 \times 10^{-2}$ and $mean\ (Std) = 25.99396 \times 10^{-2}$ respectively



(a) (b)

Figure 11. The eye of diagram (a) eye diagram like for a noisy channel ($std = 3$) and (b) corresponding QAM-16 constellation
'*' K-means referents, 'o' received noisy QAM constellation and 'x' constellation at the transmission

4. CONCLUSION

In this work, we have started our simulation by gathering all the user's information and modulating it with QAM. CDMA was then used to assign an orthogonal code to each specific user. We have used a simple orthogonal code which is the Hadamard/Welsh code. The advantage of these kinds of orthogonal codes is that the information for the intended receiver can be fully recovered just by using the transpose of the same code at the transmission. The OFDM, on the other hand, due to its spectral efficiency and its tolerance of the frequency bands overlapping, was proposed to compress the transmitted data stream to increase the data rate. Finally, we have investigated the channel transmission quality using the K-means algorithm. We believe that this method of studying the effect of channel noise on the OFDM/CDMA transmission is very useful for checking the transmission channel quality.

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The authors confirm that the research was conducted independently and without financial influence.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Abdelhamid Cherifi	✓			✓			✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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