Carrier frequency offsets problem in recent DST-SC-FDMA system: Investigation and compensation

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Abstract
Carrier frequency offset (CFO) is a challenging problem in the uplink of the single-carrier frequency division multiple access (SC-FDMA) system. CFOs effect on the orthogonality between subcarriers and cause inter-carrier interference (ICI) and multiple access interference (MAI). This paper, analyzes the impact of the CFOs on the performance of the Discrete Sine Transform (DST) SC-FDMA (DST-SC-FDMA) system and investigates with different wireless channels, different modulation schemes and different subcarriers mapping schemes. Furthermore, an efficient equalization and CFOs compensation scheme is proposed to enhance the performance of the DST-SC-FDMA system and transmit images efficiently over DST-SC-FDMA system. The proposed scheme combines the minimum mean square error (MMSE) equalizer and the parallel interference cancellation (PIC). The combined method is referred to as MMSE+PIC. The results show that CFOs degrades the DST-FDMA performance. The obtained results show a noticeable performance improvement of the proposed MMSE-PIC scheme over the conventional MMSE equalizer. Moreover, it is found that it is possible to efficiently transmit wireless image using the proposed MMSE+PIC scheme.

1 | INTRODUCTION

Modern technologies and thereby new applications are emerging to provide better services over the wireless communication. As a result, the wireless systems that are reliable and have a high spectral efficiency demandingly is required. The single-carrier frequency division multiple access (SC-FDMA) is one of the preferred chosen single-carrier transmission techniques that achieves those demands [1–3]. SC-FDMA has a similar performance to that of the orthogonal frequency division multiplexing (OFDM) system [4,5]. However, SC-FDMA, due to its inherent single carrier structure, offers a very small peak to average power ratio (PAPR) as compared to OFDM. SC-FDMA, due to its inherent properties of no interchannel interference and PAPR performance, it has been used in the uplink of long-term evolution (LTE) cellular communication systems. However, the presence of different carrier frequency offsets (CFOs) is a challenging task in SC-FDMA system due to the oscillator mismatch and/or presence of doppler shift [6,7]. CFOs affect the orthogonality between subcarriers and cause Inter-Carrier Interference (ICI) and Multiple Access Interference (MAI) among users [8]. Hence, the system performance gets deteriorated in the presence of ICI and MAI [9]. CFOs problem in multicarrier systems was extensively studied in the literature [10–12]. Feedback and compensation approaches have been proposed to reduce and mitigate the impacts of CFO when used for uplink transmission [13–15]. In our previous work [16], the impacts of CFO on SC-FDMA performance was investigated and analyzed with considering of different subcarriers mapping schemes where the localized subcarrier mapping (LFDMA) and interleaved subcarrier mapping (IFDMA) schemes are used. In [17], the effect of CFOs on SC-FDMA-IDMA was investigated with considering an uncoded system and an additive white Gaussian noise channel model.

The issue of the CFOs compensation for Discrete Fourier Transform SCFDMA (DFT-SC-FDMA) and the discrete cosine transform SC-FDMA (DCT-SC-FDMA) systems was investigated in [11] and [18]. To the best of the author’s knowledge, the issue of CFOs compensation for the DST-SC-FDMA system is not studied until the time of writing this paper. Moreover, image
transmission over DST-SC-FDMA is not studied in the literature. Motivated by these facts, we analyze and scrutinize issue of CFOs problem and its compensation in DST-SC-FDMA system. The major contributions of this work are outlined as follows:

1. A hybrid scheme comprising MMSE scheme and parallel interference cancellation (PIC) is proposed for further enhancement of CFO compensation over the DST-SC-FDMA system. This scheme is called MMSE + PIC scheme. Frequency domain linear equalization and compensation are used in our scheme. For future works, it is possible to use frequency domain decision feedback equalizer (DFE) for further improvements [19]. It is also possible to extend our work for multi-input multi-output (MIMO) SC-FDMA and use DFE [20, 21].

2. The CFOs impacts on the performance of the DST-SC-FDMA system are investigated on the basis of SNR versus BER with different wireless channels, different modulation schemes, different subcarriers mapping schemes, and the proposed MMSE + PIC and MMSE compensation techniques.

3. The peak signal to noise ratio (PSNR) and the mean square error (MSE) performances of the received image over DST-SC-FDMA system with CFO presence are studied, compared and investigated with consideration of Vehicular A channel, different modulation schemes, different subcarriers mapping schemes, and MMSE and the proposed MMSE + PIC CFO compensation techniques.

The remainder of this paper is organized as follows. In Section 2, DST-SC-FDMA system model in the presence of CFOs is introduced. In section 3, the MMSE scheme is presented. Section 4 illustrates MMSE + PIC scheme. Section 5 discusses image transmission over DST-SC-FDMA system. In Section 6, simulation results are discussed. The conclusion is presented in section 7.

## 2 DST-SC-FDMA SYSTEM MODEL IN THE PRESENCE OF CFOS

In this section, we describe the uplink DST-SC-FDMA system model in presence of CFOs.

We assume U users communicating at the same time with a fixed base station (BS) through independent multipath Rayleigh-fading channels as shown in Figure 1. The signals that are received at BS from all users are assumed to be synchronized in the time domain. The data is modulated then N-points DST is performed at the transmitter.

The output symbols of DST are mapped using interleaved and localized mapping schemes. Afterwards, an M-points inverse DST (IDST) is performed and a cyclic prefix (CP) of length $N_c$ is added to the resulting signal that is eventually transmitted over the wireless channel. The transmitted signal from the $u$th user ($u = 1, 2, \ldots, U$) can be given by [18]

$$\hat{x} = P_{\text{add}} S_{M}^{-1} B_f^T S_N x_u,$$

where $S_N$ and $S_{M}^{-1}$ are an $N \times N$ DST and an $M \times M$ IDST matrices, respectively. $B_f$ is an $M \times N$ matrix that describes the subcarriers mapping of the $u$th user. $M = Q N$, where $Q$ is the maximum number of users that can transmit, simultaneously. $x_u$ is an $N \times 1$ vector that contains the modulated symbols of the $u$th user. $P_{\text{add}}$ is an $(M + N_c) \times M$ matrix, which adds a CP of length $N_c$. as in [18], the inputs of $B_f$ matrix for both
DST-LFDMA and DST-IFDMA can be expressed in (2) and (3), respectively:

\[ B^u_f = [0_{(M-1)N \times N}; I_N^u; 0_{(M-1)N \times N}] \]  
\[ B^u_f = [0_{(M-1)N \times N}; a^u_1; 0_{(Q-2)N \times N}; \ldots; 0_{(M-1)N}; a^u_N; 0_{QN \times N}] \]

where \( I_N^u \) and \( 0_{QN \times N} \) matrices refer \( N \times N \) identity matrix and \( Q \times N \) all-zero matrix, respectively. \( u \) denotes the unit column vector, of length \( N \), with all zero entries except at \( u \). \( P_{cd} \) can be given as follows:

\[ P_{cd} = \{ C, I_M \}^T \]

where

\[ C = [0_{N \times (M-N)}, I_N]^T \]

At the receiver side, the received signal can be expressed as follows:

\[ r = \sum_{n=1}^N E^u_n H^u X^u + n \]

where \( E^u_n \) is an \( (M+N) \times (M+N) \) diagonal matrix with elements [\( E^u_n \)] \( e^{\frac{\pi}{2}} \delta_{u,m} M^{-1} \) for \( m = 1, 2, \ldots, M+N \). The CFO of the \( u \)th user for the DST-SC-FDMA system can be expressed in (2) and (3), respectively. The received signal, after the removal of the CP, can be given by:

\[ r = P_{rem} r = \sum_{n=1}^N E^u_n H^u X^u + \tilde{n} \]

where \( P_{rem} \) is an \( M \times (M+N) \) matrix that removes the CP and is expressed by

\[ P_{rem} = [0_{(M \times N)}, I_M] \]

where \( E^u_n \) is an \( M \times M \) diagonal matrix, which describes the CFO of the \( u \)th user after the CP removal. \( \tilde{n} = P_{rem} n \) and \( \tilde{X}^u = P_{rem} X^u \) are the noise and the transmitted signal after the CP removal, respectively. \( H^u \) is an \( M \times M \) circulant matrix describing the channel of the \( u \)th user.

A receiver transforms the received signal into the frequency domain via an \( M \)-points DFT as follows:

\[ R = F_M r = \sum_{n=1}^N \Gamma^u_n E^u_n X^u + N \]

where \( \Gamma^u_n = F_M E^u_n F_M^{-1} \) is a circulant matrix that represents the interference from the \( n \)th user, \( \hat{X}^u = F_M X^u \) is an \( M \times 1 \) vector that describes the transmitted samples from the \( n \)th user after the mapping process. \( N \) is the DFT of \( n \). The next step is the estimation of the modulated symbols by performing demodulation processes of the FDE, the \( M \)-points IDFT and the DST-SC-FDMA. This estimation can be given by

\[ \hat{\hat{x}}^u = S_N^{-1} B^u_R S_M F_M^{-1} W^u R \]

where \( \hat{\hat{x}}^u \) is a vector \( N \times 1 \) that contains the modulated symbols estimation. \( B^u_R \) is an \( N \times M \) subcarriers demapping matrix of the \( n \)th user. The entries of \( B^u_R \) for both DST-LFDMA and DST-IFDMA systems are determined by using the transpose of Equations (2) and (3), respectively. \( W^u \) is an \( M \times M \) matrix that represents FDE of the \( n \)th user. In the last step, the decoding and the demodulation processes are performed.

3 THE MMSE SCHEME

MMSE scheme is shown in Figure 2. The MMSE matrix of the joint scheme can be expressed in the frequency domain by using [18]:

\[ R = F_M r = \Gamma_{\hat{x}}^u X^u + \sum_{n=1}^N \Gamma^u_n X^u + N \]

where \( \Gamma_{\hat{x}}^u \) is the \( N \times N \) circulant CFOs interference matrix of the \( k \)th user. The error \( e \) between the estimated symbols \( \hat{X}^u \) and the transmitted symbols \( X^u \) can be defined as follows:

\[ e^k = W^k R - \hat{X}^k \]

The equalizer matrix of the \( k \)th user is obtained by cost function of the minimization of the mean square error (MSE) as follows:

\[ J_k = E \{ || e^k ||^2 \} = E \{ || W^k R - \hat{X}^k ||^2 \} \]

where \( E \) refers to expectation of \( || W^k R - \hat{X}^k ||^2 \) term. The MMSE is determined by solving \( dJ_k / \partial W^k = 0 \) as follows:

\[ W^k = \Gamma_{\hat{x}}^k \left( \Gamma_p^k \Sigma_p^{-1} + 1/(SNR) \right)^{-1} \]

where \( \Gamma_{\hat{x}}^k = \Gamma_{\hat{x}}^u \Lambda^k \).

The estimated frequency domain symbols of the \( k \)th user are transformed into time domain symbols as follows:

\[ \hat{x}^k = S_N^{-1} B^u_R S_M F_M^{-1} W^u R \]
For the proposed MMSE scheme, the inversion of an $M \times M$ matrix for each user is required, which is practically difficult for a large $N$. The required complexity on the order of $O(M^3)$, which is large for a large number of subcarriers. However, it is important to note that most of the elements in $\Gamma^k_e$ are zeros and this matrix can be approximated as a banded matrix [11]. Thus, the total number of operations required in the banded matrix implementation for the DST-SC-FDMA system is approximately $M[16r^2 + 26r + 5]$, where $r$ is the bandwidth of a banded matrix.

### 4 MMSE+PIC Scheme

In this section, we propose a MMSE+PIC scheme which is the combination of joint MMSE equalizer and CFOs with PIC to further reduce the effect of the residual MAI on the DST-SC-FDMA system. The structure of the proposed MMSE+PIC scheme for DST-SC-FDMA system is shown in Figure 3. In this scheme, the MMSE equalizer is used to estimate the MAI interference, which is regenerated and removed from the original received signal using the PIC in the frequency domain.

The algorithm of the proposed MMSE+PIC scheme for uplink DST-SC-FDMA system can be summarized as follows:

**Algorithm:**

1. Remove CP from the received signal by using (7).
2. Apply DFT to the output signal using (9).
3. Apply joint MMSE scheme to estimate the samples for each user using (10).
4. Transform frequency domain estimates of the interfering users’ samples into time domain symbols and $M$-point DST, subcarrier demapping, $N$-point IDST and the decision function $f_{dec}$, hard decision function, is applied as follows:

$$\hat{x}^k = f_{dec}(S_N^{-1}B_N^k S_M F_N^{-1} W^k \hat{X}^k) \quad (16)$$

5. Regenerate MAI in the frequency domain as follows:

$$\mathbf{R}_{MAI}^k = \sum_{\nu \neq k} U \nu \mathbf{A}^\nu F_N S_M^{-1} B_N^\nu S_N \hat{x}^\nu \quad (17)$$
6. Subtract MAI from \( \mathbf{R} \) to get the frequency domain interference-free signal as follows:

\[
\mathbf{R}_{\text{free}}^k = \mathbf{R} - \mathbf{R}^k_{\text{MAI}}
\]  

(18)

7. Estimate the frequency domain samples by applying the MMSE scheme, N-point IDFT, M-point DST, subcarrier demapping and N-point IDST on the interference-free signal \( \mathbf{R}_{\text{free}}^k \) as follows:

\[
\hat{x}^k = S^{-1}_N B^k S_M F^{-1}_N W^k \mathbf{R}_{\text{free}}^k
\]  

(19)

8. Finally, apply the demodulation, and decoding processes to provide a better estimate of the desired data.

The main advantage of the proposed MMSE+PIC scheme is its better BER performance, even at high CFOs. However, the complexity of the receiver as compared with the MMSE receiver, which is the base station, will be increased.

5 | IMAGE TRANSMISSION

For more investigation and in order to evaluate the proposed cancellation technique over DST-SC-FDMA, multi-user image transmission has been conducted in terms MSE and PSNR metrics. The quality of the reconstructed image with the original transmitted image is compared. The standard image “Cameraman image” will be transmitted over DST-SC-FDMA system with different basis functions, different subcarriers mapping schemes, different modulation schemes, and MMSE and MMSE+PIC compensation techniques.

PSNR is the ratio between the maximum possible power of a signal and the power of the corrupting noise that affects the fidelity of this signal. It can be given by the following formula [12]:

\[
\text{PSNR} = 10 \log \left( \frac{f_{\text{max}}^2}{\text{MSE}} \right)
\]  

(20)

where \( f_{\text{max}}^2 \) is the maximum pixel value in the image. On the other hand, the MSE is can be obtained as follows [12]:

\[
\text{MSE} = \frac{1}{M^2} \sum_{i=1}^{M} \sum_{j=1}^{M} (I_o(i,j) - I_r(i,j))^2
\]  

(21)

where \( M \) is number of pixels and \( I_o \) and \( I_r \) are the transmitted and the received images, respectively. The transmitted Cameraman image for all users of size 256 × 256 is shown in Figure 4.

6 | SIMULATION RESULTS

Experiments and results have been carried out by using MATLAB simulator to mainly study the effectiveness of CFOs on the uplink DST-SC-FDMA with different modulation schemes, different subcarriers mapping schemes, different channels and MMSE and MMSE+PIC compensation techniques. For more accurate and clear, the performance of DST-SC-FDMA systems without CFOs and without CFOs compensation techniques is evaluated. The Monte Carlo simulation method is used to evaluate the achievable SNR versus BER. Independent CFOs are assumed for all uplink users. Each CFO is random variable with uniform distribution in \([-0.3,0.3]\). The CFOs are chosen randomly to simulate more practical scenario. This section is divided into five subsections. The first subsection presents the simulation parameters, the second subsection discusses the impact of CFOs on DST-SC-FDMA system, the third subsection shows SNR vs BER simulation, the fourth subsection contains the simulation results of image transmission over the DST-SC-FDMA system, and finally the fifth subsection presents clarity investigation of the image transmission over DST-SC-FDMA system.

6.1 | Simulation parameters

Uplink DST-SC-FDMA system with 128 subcarriers are considered. In these systems, four users are assumed with 32 subcarriers allocation to each user. QPSK and 16-QAM mapping are employed for data symbols of all users. The vehicular A and SU13 models are used as channel models. The channel code that is used for the simulation is convolutional code with memory length 7 and octal generator polynomials (133,171). The simulation parameters are listed in Table 1.

6.2 | Impact of the CFOs

Figures 5 and 6 show that BER as a function of the maximum normalized CFO for the DST-IFDMA and DST-LFDMA systems at different values of the SNR, respectively. To further clarify demonstrate the feasibility of the results, independent
TABLE 1  Simulation parameters

| The parameter          | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| Simulation method      | Monte Carlo                                                                 |
| System bandwidth       | 5 MHz                                                                       |
| Modulation type        | QPSK and 16-QAM                                                             |
| CP length              | 20 samples                                                                  |
| M                      | 128                                                                          |
| N                      | 32                                                                           |
| Channel coding         | Convolutional code with rate = 1/2                                          |
| Subcarriers mapping technique | Interleaved and localized                                              |
| CFOs                   | Random                                                                      |
| U                      | 4                                                                           |
| Channel model          | Vehicular A channel and SUI3                                                 |
| CFOs estimation        | Perfect                                                                     |
| Channel estimation     | Perfect                                                                     |

FIGURE 5  BER versus maximum CFO ($\delta_{\text{max}}$) for the DST-IFDMA system

FIGURE 6  BER versus maximum CFO ($\delta_{\text{max}}$) for the DST-LFDMA system

FIGURE 7  BER versus SNR for the DST-IFDMA over a Vehicular A channel when the QPSK is used

FIGURE 8  BER versus SNR for the DST-LFDMA over a Vehicular A channel when the QPSK is used

CFOs are considered for all uplink users. These figures show that the performance of the MMSE+PIC scheme is better than the MMSE scheme, especially at the large values of CFOs.

6.3  BER versus SNR simulation

This subsection presents the BER versus SNR simulation with considering QPSK and 16-QAM modulation techniques.

6.3.1  QPSK modulation

Figures 7 and 8 show the performance of the DST-IFDMA and DST-LFDMA systems with considering the QPSK modulation scheme over a Vehicular A channel. It is noted that the two CFOs compensation schemes (MMSE and MMSE+PIC) are able to eliminate the effect of the CFOs. From these figures, it is clear that the MMSE+PIC can avoid the MAI and provide better BER performance than the MMSE scheme and its performance is close to the system without CFOs. This is due to the ability of the MMSE+PIC scheme to effectively eliminate the MAI. It can be also seen that the MMSE+PIC scheme for the DST-LFDMA system that shown in Figure 8 provides the same BER performance as without CFOs, while
for the DST-IFDMA system it suffers 1.5 dB loss in the BER performance at \(10^{-4}\) as compared to that without CFOs shown in Figure 7. Furthermore, it is noted that MMSE scheme suffers 2 and 3.5 dB loss in the BER performance at \(10^{-4}\) for the DST-LFDMA and DST-IFDMA systems, respectively, as compared to that without CFOs.

In the DST-IFDMA system that are shown in Figure 7, for BER = \(10^{-4}\), the SNR values equal 20 and 22 dB for MMSE+PIC and MMSE, respectively whereas in the DST-LFDMA system shown in Figure 8, the SNR value equals 21.8 and 25 dB for MMSE+PIC and MMSE respectively, so the DST-IFDMA system is better than the DST-LFDMA system.

For comparison purposes, the performance of the DST-IFDMA and DST-LFDMA system over SU13 channel are simulated in Figures 9 and 10, respectively. It is clear that the DST-IFDMA system performance by using SU13 channel is better than using a Vehicular A channel. In the DST-IFDMA system that are shown in Figure 9, for BER = \(10^{-4}\), the SNR values equal 14 dB and 19 dB for MMSE+PIC and MMSE, respectively whereas in the DST-LFDMA system that shown in Figure 10, the SNR values equal 17 dB for both schemes which is more better than that in a Vehicular A channel.

### 6.3.2 16-QAM modulation

The performance of the DST-IFDMA and DST-LFDMA system over a Vehicular A channel for 16-QAM Modulation scheme are shown in Figures 11 and 12, respectively.

From Figure 12, it can be observed that the MMSE+PIC scheme for the DST-LFDMA system provides the same BER performance as without CFOs, while for the DST-IFDMA system it suffers 2 dB loss in the BER performance at BER = \(10^{-2}\) as compared to that without CFOs as shown in Figure 11. Furthermore, it is noted that the MMSE scheme suffers 0.3 dB loss in the BER performance at BER = \(10^{-2}\) for the DST-LFDMA and about 4 dB loss in the BER performance at BER = \(10^{-1}\) and more than that at BER = \(10^{-2}\) for the DST-IFDMA systems as compared to that without CFOs. As compared to QPSK modulation that is shown in Figures 7 and 8, it is clear that the QPSK modulation type has the best BER performance but it is known that the data rate of 16-QAM modulation is the best. So, there is a trade-off between the high data rate and the good performance. At an SNR = 20 dB, the BER = \(3 \times 10^{-2}\) and \(10^{-1}\) for the MMSE+PIC and MMSE scheme in the DST-IFDMA system as shown in Figure 11, respectively. For the DST-LFDMA system that is shown in Figure 12, the BER for the MMSE+PIC scheme is equal to
so the localized system is better than the interleaved system.

Figures 13 and 14 show the performance of the DST-IFDMA and DST-LFDMA systems for 16-QAM modulation scheme over SUI3 channel, respectively. It is noted that the performance of the DST-SC-FDMA system over SUI3 channel is better than that in the Vehicular A channel. At an SNR = 20 dB, the BER = 2.5 × 10⁻² but for the MMSE scheme it is equal to 3 × 10⁻² so the localized system is better than the interleaved system.

6.4 | PSNR performance

As mentioned, for more investigation and in order to evaluate the proposed cancellation technique over DST-SC-FDMA, image transmission has been conducted in terms of MSE and PSNR metrics. For this purpose, Cameraman image has been transmitted over the coded DST-SC-FDMA system in the presence of CFOs with considering Vehicular A channel model, different subcarriers mapping schemes, QPSK and 16-QAM modulation schemes, and MMSE and MMSE+PIC compensation techniques. PSNR values of the received image are calculated for different SNR values from 0 through 30 dB with 5 dB steps.

The obtained values of PSNR are tabulated in Tables 2 and 3 for QPSK and 16-QAM modulation schemes and illustrated in Figures 15 and 16, respectively.

Figures 15 and 16 show the relationship between PSNR and SNR when Cameraman image is transmitted through the DST-SC-FDMA system for different subcarriers mapping schemes when QPSK and 16-QAM modulation schemes are used, respectively. As illustrated in both figures, it is observed that PSNR increased as SNR increased. Clearly, it is observed that the interleaved system gives better PSNR performance than the localized system for both CFOs compensation schemes when the QPSK is used as shown in Figure 15. Adversely, it is noted that the localized system gives better PSNR performance than the interleaved system when 16-QAM is used as shown in Figure 16. It can be also seen that the MMSE+PIC scheme provides better performance than the MMSE scheme. As
TABLE 2  PSNR values of the received Cameraman image over the DST-SC-FDMA systems when QPSK is used

| SNR (dB) | MMSE | MMSE+PIC | Without compensation | Without CFO |
|----------|------|----------|----------------------|-------------|
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |

TABLE 3  PSNR values of the received Cameraman image over the DST-SC-FDMA systems when 16 QAM is used

| SNR (dB) | MMSE | MMSE+PIC | Without compensation | Without CFO |
|----------|------|----------|----------------------|-------------|
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |
|          |      |          |                      |             |

compared to the 16-QAM modulation scheme, the QPSK modulation scheme has the best PSNR performance.

6.5  MSE performance

In this section, the MSE performance is examined and investigated. As in PSNR performance evaluation, Cameraman image has been transmitted over the coded DST-SC-FDMA system in the presence of CFOs with considering Vehicular A channel model, different subcarriers mapping schemes, QPSK and 16-QAM modulation schemes, and MMSE and MMSE+PIC compensation techniques. The obtained values of MSE are tabulated in Tables 4 and 5 and illustrated in Figures 17 and 18, respectively.

Figures 17 and 18 illustrate the relationship between MSE and SNR when Cameraman image is transmitted through the considered system. It is observed that the MSE decreases when SNR increases. However, it is observed that the interleaved systems give lower values of MSE than the localized systems when the QPSK is used. In contrary, it is observed that the localized systems give lower values of MSE than the interleaved systems when the 16-QAM is used. It can be also seen that the MMSE+PIC scheme gives better performance than the MMSE scheme. As compared to the 16-QAM modulation scheme, the QPSK modulation scheme has the best MSE performance.

6.6  Clarity investigation

To investigate the clarity of the received images over the considered system, the received images at an SNR = 25 dB are selected. Figure 19 shows the received images of the DST-SC-FDMA system without CFOs for QPSK and 16-QAM. To clarify the quality of the received image over the system, the reconstructed images at an SNR = 25 dB with QPSK and 16-QAM are shown in Figures 20 and 21, respectively. By comparing the received images with the images shown
TABLE 4

| SNR (dB) | MSE MMSE PIC | MSE MMSE PIC | MSE MMSE PIC | MSE MMSE PIC |
|----------|--------------|--------------|--------------|--------------|
| 0        | 0.1095       | 0.1071       | 0.1041       | 0.1011       |
| 5        | 0.0532       | 0.0515       | 0.0511       | 0.0507       |
| 10       | 0.0118       | 0.0114       | 0.0114       | 0.0112       |
| 15       | 0.0025       | 0.0026       | 0.0026       | 0.0025       |
| 20       | 0.0080       | 0.0080       | 0.0080       | 0.0080       |
| 25       | 0.0256       | 0.0256       | 0.0256       | 0.0256       |
| 30       | 0.0558       | 0.0558       | 0.0558       | 0.0558       |

FIGURE 18
MSE versus SNR of the Cameraman image transmission over the DST-SC-FDMA system when the 16-QAM is used.

In Figure 19, it is concluded that the quality of the received image by using the MMSE-PIC scheme to compensate the CFOs is better than those images that are received by using the MMSE scheme. It is clear that the QPSK modulation scheme has better quality than the 16-QAM modulation scheme. It can be also seen that the interleaved system is better than the localized system when the QPSK is used but the localized system is better than the interleaved system when the 16-QAM is used.

7 | CONCLUSION

This paper investigated the performance of the DST-SC-FDMA system in the presence of CFOs for different wireless channels, QPSK and 16-QAM modulation schemes, and different subcarriers mapping. CFOs compensation scheme has also been proposed that are referred to as MMSE+PIC. For more comparison, the obtained results with the MMSE scheme, without CFO and without CFO compensation have been simulated. It has been found that the performance of the DST-SC-FDMA degrades due to the CFOs and an efficient CFOs compensation scheme must be used. Simulation results have shown that the proposed MMSE+PIC improves the performance of the DST-SC-FDMA system for different modulation schemes, different wireless channels and different subcarriers mapping. Results also showed that the performance of the DST-IFDMA system is better than that of the DST-LFDMA system when QPSK is used but when 16-QAM is used, the performance of the DST-LFDMA system is better than that of the DST-IFDMA system. For more evaluation, the performance of the DST-SC-FDMA system in the presence of CFOs has been tested with image transmission over a Vehicular A channel for different scenarios. The obtained results show a noticeable performance improvement of the proposed MMSE+PIC scheme over the conventional MMSE scheme. This indicates that it is possible to efficiently transmit images over DST-SC-FDMA using the proposed MMSE+PIC scheme.
| SNR(dB) | MMSE | MMSE-PIC | Without compensation | Without CFO |
|--------|------|----------|----------------------|-------------|
|        | LFDM | IFDMA    | LFDM | IFDMA | LFDM | IFDMA | LFDM | IFDMA |
| 0      | 0.1290 | 0.1291 | 0.1303 | 0.1316 | 0.1320 | 0.1315 | 0.1287 | 0.1305 |
| 5      | 0.1020 | 0.1083 | 0.1010 | 0.1109 | 0.1090 | 0.1138 | 0.1016 | 0.1082 |
| 10     | 0.0614 | 0.0693 | 0.0591 | 0.0721 | 0.0819 | 0.0835 | 0.0597 | 0.0646 |
| 15     | 0.0307 | 0.0325 | 0.0269 | 0.0327 | 0.0575 | 0.0562 | 0.0271 | 0.0244 |
| 20     | 0.0105 | 0.0115 | 0.0071 | 0.0094 | 0.0402 | 0.0388 | 0.0073 | 0.0051 |
| 25     | 0.0039 | 0.0055 | 0.0011 | 0.0027 | 0.0341 | 0.0324 | 0.0012 | 9.3488e-04 |
| 30     | 0.0031 | 0.0040 | 2.9689e-04 | 0.0014 | 0.0326 | 0.0311 | 3.2699e-04 | 2.8068e-04 |

**TABLE 5** MSE values of the received Cameraman image over the DST-SC-FDMA systems when 16 QAM is used

**FIGURE 19** Received Images for DST-SC-FDMA system without CFOs at an SNR = 25 dB

(a) Interleaved QPSK  
(b) Localized QPSK  
(c) Interleaved 16-QAM  
(d) Localized 16-QAM
Figure 20: Received Images for DST-SC-FDMA system at an SNR = 25 dB and QPSK.
FIGURE 21  Received Images for DST-SC-FDMA System at an SNR = 25 dB and 16-QAM
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