CARRIER FREQUENCY SYNCHRONIZATION FOR OFDM-IDMA SYSTEMS

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Abstract: The recently proposed Orthogonal Frequency Division Multiplexing-Interleave Division Multiple Access (OFDM-IDMA) scheme has been at the forefront of wireless communication systems research due to its promising features which include high efficiency, flexibility and high data-rate wireless transmission. Earlier, major research on this new scheme had only focused on the perfect-condition scenarios, with the assumption that the system is free from synchronization errors. However, recent studies show that synchronization errors, especially the carrier frequency offsets, have significant impact on the OFDM-IDMA systems. This work therefore examines comprehensively, analyses and verifies the impact of synchronization errors on the performance of the OFDM-IDMA hybrid multicarrier scheme. Furthermore, simple but effective synchronization algorithms, namely; the linear minimum mean-squared error (MMSE) based algorithm, and the Kernel Least Mean Square (KLMS) algorithm as well as its normalized counterpart called the Normalized-KLMS are adopted and adequately exploited to combat the degrading impacts of synchronization errors on the OFDM-IDMA scheme. The linear minimum mean-squared error (MMSE) based algorithm, is a non-data aided method, which focuses on the mitigation of the inter-channel interference induced by the effect of synchronization errors on the system. The Kernel Least Mean Square (KLMS) algorithm, as well as its normalized counterpart, presents an efficient approach for estimation and effective correction methods to combat the effect of carrier frequency offset errors on the performance of the OFDM-IDMA system. The bit error rate (BER) performance of these algorithms is presented, compared, and analyzed. Also, the achievable performance of these synchronization algorithms in a Rayleigh multipath channel scenario with varying mobile speed is analyzed and documented.

Keywords: IDMA, OFDM-IDMA, KLMS, MMSE, CFO, synchronization

1. INTRODUCTION

The demand for a reliable and high-data-rate mobile communication service has been phenomenal in recent decades. This has necessitated several research works in advanced communication techniques to serve this unprecedented demand, while also tackling the challenges associated with mobile communications, which include multipath fading, co-channel interference, and Doppler Effect among others.

Various techniques have been studied to proffer solutions to these wireless communication challenges. Prominent among these techniques are Orthogonal Frequency Division Multiplexing (OFDM) and the Code Division Multiple Access (CDMA) multiuser schemes. Both schemes offer a number of advantages but it is noteworthy that the combined scheme of OFDM-CDMA appears most attractive due to its high spectral efficiency and radio resource management flexibility. However, the multicarrier CDMA scheme [1] faces a major challenge in Multiple Access Interference (MAI) at the receiver. This causes degradation in performance of the system. This becomes even more severe as the number of active users increases. Multiuser detection (MUD) techniques, which are usually deployed at the receiver end of the system, involving the removal of interfering signals from the signal of interest, have been widely employed to tackle MAI in OFDM-CDMA systems [2, 3]. Several MUD techniques have been studied with the aim of achieving a reasonable level of complexity with some compromise in the system performance. However, the complexity of these detection schemes tends to grow exponentially as the number of users increases.

A new multiuser scheme called Interleave Division Multiple Access (IDMA), with associated low complexity in comparison with the OFDM-CDMA scheme was proposed in 2002 by Li Ping et al [4]. A combined scheme of OFDM-IDMA was later proposed in 2006 by Mahafeno et al. [5] to enhance the performance of the conventional IDMA scheme, although a related technique had been proposed earlier by Xibin Xu et al [6] but with major attention on the downlink scenario. The study by Mahafeno et al. evaluated the performance of the OFDM-IDMA scheme in a perfectly synchronous scenario and presented a comparison between the conventional IDMA and the OFDM-IDMA scheme. In Fig. 1, the block diagram of a conventional IDMA transceiver is shown. The OFDM-IDMA transceiver, as shown in Fig. 2, is similar to Fig. 1 but for the insertion of the OFDM component in the system. A simple chip-by-chip iterative multiuser detection strategy is employed for the implementation of the multiuser IDMA scheme [7]. The major priority of the OFDM-IDMA scheme is to mitigate MAI and Inter-symbol Interference (ISI) with low complexity. Comparisons are made between the multiple access schemes IDMA and CDMA in [8, 9]. The OFDM-IDMA scheme offers a better system performance and higher spectral efficiency than the conventional multicarrier CDMA scheme, combining all the inherent advantages of the OFDM and the IDMA schemes. The OFDM-IDMA enables high flexibility of resource allocation among users and the MUD in this scheme can be implemented efficiently with complexity per user independent of the channel length and the number of users [10, 11].

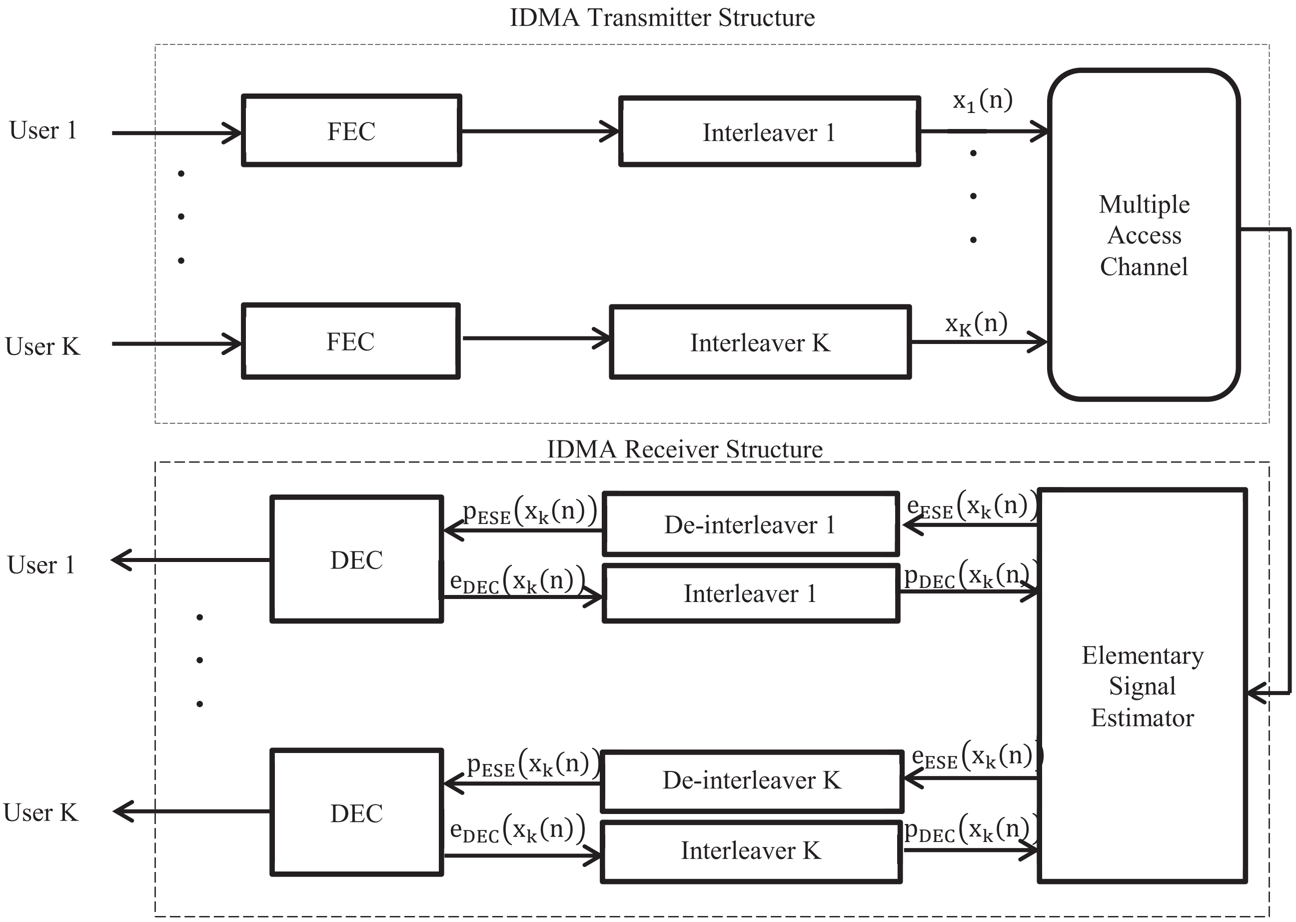

Fig. 1 Block diagram of a typical IDMA Transceiver.

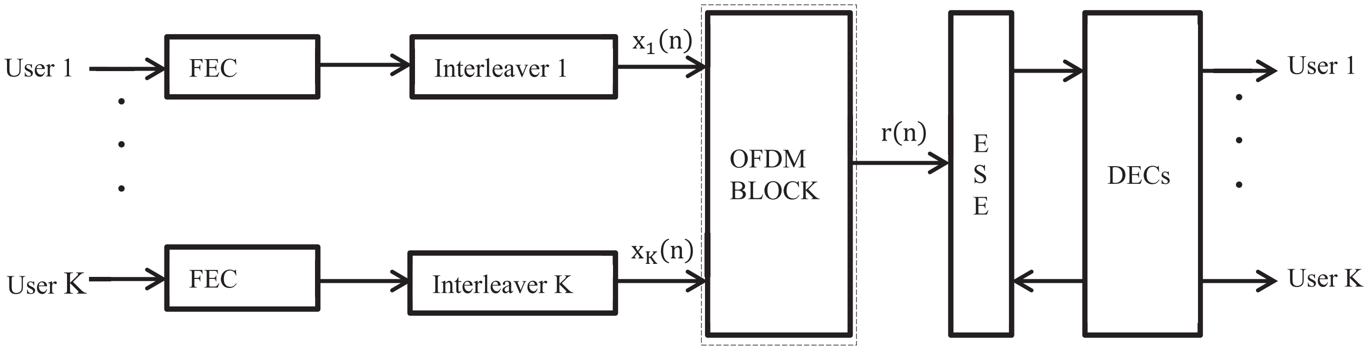

Fig. 2 The block representation of the OFDM-IDMA Transceiver.

However, recent studies [12, 13, 14] show that the presence of the OFDM component makes the OFDM-IDMA scheme vulnerable to synchronization errors. The OFDM technique is highly sensitive to carrier frequency offsets (CFOs) especially when users are transmitting asynchronously with diverse delays and fading at the uplink. Doppler Shifts and instabilities in the local oscillators are the major cause of carrier frequency offsets [15], which cause Inter-channel Interference (ICI) and loss of orthogonality among the sub-carriers, leading to an overall performance degradation of the system.

The contribution of this paper therefore, is to examine, analyze, and verify the impact of synchronization errors on the performance of the recently proposed multicarrier IDMA scheme. The impact of synchronization errors on the multicarrier scheme is investigated in both slow fading and fast fading multipath channel. Also, much has not been done hitherto to address the degrading effect of synchronization errors, especially the carrier frequency offset errors on the performance of this noble scheme. Hence, we present and implement a linear Minimum Mean-squared Error (MMSE) based algorithm as well as the Kernel Least Mean Square (KLMS) synchronization algorithms to combat the undesirable impact of synchronization errors on the overall performance of the OFDM-IDMA scheme. To the best of our knowledge, the proposed algorithms have not been exploited and jointly studied in literature, to tackle synchronization errors in multicarrier IDMA systems. Furthermore, computer simulations are presented and the algorithms are applied in a Rayleigh fading multipath channel with varying mobile speed to verify their effectiveness and to clearly demonstrate their influence on the performance of the OFDM-IDMA system in a practical scenario. Also, the algorithms are comprehensively compared to ascertain which of the algorithms offer the most efficient system performance.

The layout of the rest of the paper is as follows: Section 2 describes the conventional system model of the OFDM-IDMA scheme as well as in the presence of CFOs. Section 3 presents the proposed carrier frequency synchronization algorithms; the linear MMSE-based algorithm and the KLMS synchronization algorithms. Section 4 discusses and analyses the simulation results and lastly in Section 5, the conclusion is given.

2. THE MULTICARRIER IDMA SYSTEM MODEL

The multicarrier IDMA scheme is a combination of two different mobile communication techniques. These are the Orthogonal Frequency Division Multiplexing (OFDM) and the Interleave Division Multiple Access (IDMA) techniques. The OFDM-IDMA scheme was proposed in a bid to improve the performance of the conventional IDMA, proffering a host of advantages, which include high spectral efficiency, low receiver complexity, robustness against fading caused by multipath, among others.

2.1 The conventional OFDM-IDMA transceiver

The OFDM technique [16], essentially involves the division of high data rate streams into parallel streams of a lower data rate which are modulated by different narrowband sub-carriers and then transmitted. This technique takes care of the problems of Inter-symbol Interference and Inter-channel Interference, which are encountered while transmitting streams of high data rate. However, orthogonality must be maintained between sub-carriers to avoid interference and enable good signal reception at the receiver. The IDMA multiuser technique essentially involves the assignment of distinct interleavers, which are randomly generated, to distinguish signals from different users unlike the CDMA technique where spreading codes are used as the main identifiers in the system.

Considering the transceiver structure of the OFDM-IDMA system, as shown in Fig. 2 with K users communicating concurrently, the input data of a particular user k, is first encoded using a Forward Error Correction (FEC) code [17, 18] then interleaved by a randomly generated interleaver to obtain $x_k(n)$. The Forward Error Correction codes replace the spreading codes needed for reliable data transmission and reception in the multicarrier CDMA scheme. The FEC technique increases the coding gain of the OFDM-IDMA scheme and controls errors in the information transmitted over the fading channel. The signal, which results from the interleaving process, is transmitted over the multipath channel to the receiver. The received signal is given as:

$$r(n) = \sum_{k=1}^{K} x_k(n) \otimes h_k(n) + j(n), \qquad (1)$$

$$= x_k(n) \otimes h_k(n) + \lambda_k(n), \qquad (2)$$

where $h_k(n)$ is the multipath channel coefficient, $j(n)$ is the additive white Gaussian noise (AWGN) and the combination of the interference due to other simultaneous users, with respect to a particular user k and the Gaussian noise $j(n)$ is represented by $\lambda_k(n)$, and can be written as:

$$\lambda_k(n) = \sum_{k' \neq k} x_{k'}(n) h_{k'}(n) + j(n), \qquad (3)$$

Also present at the receiver end of the OFDM-IDMA system are the Elementary Signal Estimator (ESE), which is of low complexity, and *a posteriori probability* (APP) decoder [19] for each of the users. The ESE function operates in a chip-by-chip sequence, as detailed in [19, 20].The ESE mainly carries out a low computational chip-by-chip detection to coarsely subtract interference among concurrent users in the system. The mean and variance for each chip, as computed by the APP decoders, are iteratively fed back to the ESE unit. This is an important process which enables the ESE unit to provide a better output as well as to obtain an improved APP estimation. Now considering a system in which the BPSK signaling is assumed and chip-by-chip detection takes place in a quasi-static multipath channel, the interference mean and the variance are therefore estimated as [21]:

$$E\big(\lambda_k(n)\big) = E\big(r(n)\big) - h_k(n)E\big(x_k(n)\big), \qquad (4)$$
$$Var\big(\lambda_k(n)\big) = Var\big(r(n)\big) - |h_k(n)|^2 Var\,\big(x_k(n)\big). \qquad (5)$$

From the interference mean and variance expressed above, the output of the ESE for an active user k is derived, based on the extrinsic log-likelihood ratios (LLRs) generation, as follows [21]:

$$e_{ESE}\big(x_k(n)\big) = 2h_k(n)\frac{r(n)-E(\lambda_k(n))}{Var(\lambda_k(n))}. \qquad (6)$$

All derivations above represent an ideal situation where it is assumed that the OFDM-IDMA system is perfectly synchronized, with no errors. However, this is not feasible in practice where active users transmit asynchronously with diverse delays and fading at the uplink. These lead to the loss of orthogonality and subsequently, degrades the overall output of the system.

2.2 The OFDM-IDMA System analysis with carrier frequency offsets

Major studies on the OFDM-IDMA scheme have been considered under perfect conditions, without considering the impact of carrier frequency offsets on the overall performance of the system. However, as studied recently by some papers [12, 13, 14], the OFDM-IDMA scheme suffers from carrier frequency offset (CFO) errors, a problem inherent in the OFDM component, causing high performance degradation in the system. Synchronization errors cause Inter-channel interference and loss of orthogonality among the sub-carriers, which in turn causes performance degradation.

Therefore, considering the scenario where carrier frequency offsets (CFOs) are introduced into the system, equation *(1)* then becomes:

$$r_{se}(n) = \sum_{k=1}^{K}(x_k(n) \otimes h_k\,(n))e^{j2\pi\varepsilon_k n/N} + z(n)\,, \qquad (7)$$

where *n* represents the sub-carrier index, *N* is the number of sub-carriers and ε_k, $\varepsilon_k \ll 0.5$ [22], represents the normalized CFO. After the discrete Fourier transforms operation, equation *(7)* becomes:

$$R_{se}(m) = \sum_{n=0}^{N-1} r_{se}(n)e^{-j2\pi\varepsilon_k m/N}. \qquad (8)$$

The mathematical expression in equation *(8)* can therefore be represented, with respect to other simultaneous users as:

$$R_{se}(m) = X_k(m)H_k(m) + \sum_{k'\neq k} X_{k'}\,(m)H_{k'}(m) + \mathfrak{z}_k(m) + Z(m), \qquad (9)$$

and the overall interference in the OFDM-IDMA system, symbolized by $\lambda'_k(m)$, is written as:

$$\lambda'_k(m) = \sum_{k'\neq k} X_{k'}\,(m)H_{k'}(m) + \mathfrak{z}_k(m) + Z(m), \qquad (10)$$

where $Z(m)$ is a Gaussian random variable expressed as:

$$Z(m) = \sum_{n=0}^{N-1} j(n)e^{-j2\pi n(m-\varepsilon_k)/N}, \qquad (11)$$

while the interference due to the carrier frequency offset between a particular user k denoted as ε_k and another active user k' indicated as $\varepsilon_{k'}$ is represented by $\mathfrak{z}_k(m)$. The mathematical expression of the interference $\mathfrak{z}_k(m)$ is therefore given as [12]:

$$\mathfrak{z}_k(m) = \sum_{n=0}^{N-1} e^{j2\pi n(\varepsilon_{k'}-\varepsilon_k)/N}. \qquad (12)$$

From equations *(4)* and *(5)*, having in mind that carrier frequency offsets are now introduced into the system and also modifying equation *(6)*, the output of the elementary signal operator, in a multipath channel, based on the extrinsic log-likelihood ratios (LLRs) generation [21], therefore becomes:

$$e'_{ESE}\big(X_k(m)\big) = 2H_k(m)\frac{R_{se}(m)-E(\lambda'_k(m))}{Var(\lambda'_k(m))}\,. \qquad (13)$$

Hence, the equations above establish the presence and the effect of carrier frequency offset in the OFDM-IDMA system model. Addressing the degrading impact of synchronization errors is therefore crucial for optimum performance and system efficiency.

3. CARRIER FREQUENCY SYNCHRONIZATION

Carrier frequency offsets have critical influence on the overall efficiency of the multicarrier IDMA scheme as described above. A linear MMSE-based synchronization algorithm, which is a non-data aided technique, as well as the KLMS algorithm are therefore presented and implemented to combat the deteriorating effect of carrier frequency offset errors on the performance of the OFDM-IDMA system.

3.1 The MMSE-Based Synchronization Algorithm

The CFO of a particular user k can be compensated coarsely in the time domain of the multicarrier IDMA system. The received signal can be multiplied by the complex exponent of the offset estimate, in the presence of carrier frequency offsets, as seen in equation *(7)*, to achieve a coarse error compensation for an active user. However, the main challenge is the Inter-channel interference which results from the residual CFOs due to other simultaneous active users in the system. The focus of this MMSE-based synchronization algorithm is therefore to reduce the effect of the ICI originating from the residual CFOs of concurrent users in the OFDM-IDMA system. Hence, the proposed linear MMSE-based algorithm is obtained by computing the second order statistics from equations *(8), (11),* and *(12)* as [23]:

$$E(|R_{se}(m)|^2) = \frac{1}{N}E\left(\left|\sum_{n=0}^{N-1}\big(x_k(n) \otimes h_k(n)\big)e^{\frac{j2\pi\varepsilon_k n}{N}}e^{-\frac{j2\pi\varepsilon_k m}{N}}\right|^2\right)$$

$$+E(|Z(m)|^2), \tag{14}$$

$$= \frac{1}{N}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} E\Big(\big(x_k(m)\otimes h_k(m)\big)(x_k(n)\otimes h_k(n))^*\Big) \\ .\, e^{-j2\pi\varepsilon_k(m-n)/N} + N_0/2,$$

$$= \frac{1}{N}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1}\cdot\Big[\sum_{l=0}^{N-1} E(|H_l|^2)E(|X_l|^2)e^{j2\pi l(m-n)/N}\Big] \\ .\, e^{-j2\pi\varepsilon_k(m-n)/N} + N_0/2,$$

$$= S_s|H|^2 + N_\Theta/2, \tag{15}$$

where S_s is the data symbol energy with sub-carrier length l , and $N_\Theta/2$ is the power spectral density.

From equations *(9)* and *(15)*, the power of the ICI term is therefore derived as stated below [23]:

$$E(|\,\text{ʓ}_k(m)|^2) = E(|R_{se}(m)|^2) - E(|\,Z(m)|^2) \\ -E(|X_k(m)H_k(m)|^2)sinc^2(\varepsilon_k), \tag{16}$$

$$= S_s|H|^2\big(1 - sinc^2(\varepsilon_k)\big). \tag{17}$$

In equation *(17)*, the presence of CFO ε_k is visible and the ICI power will have its minimum value at $\varepsilon_k = 0$. Also, the power of the ICI in the OFDM-IDMA system will increase as the value of the CFO ε_k increases. Therefore, the impact of carrier frequency offset errors can be mitigated adequately by reducing the spectral power of the ICI in the OFDM-IDMA system. To achieve this, the following cost function stated below can be employed [23, 24]:

$$P_c(m) = \frac{1}{M}\sum_{k=0}^{M-1} E\big((|R_{se}(m)|^2 - E^2)^2\big), \tag{18}$$

where E^2 is the expectation of $|R_{se}(m)|$ taken to ensure the cost function $P_c(m)$ is minimized for carrier frequency value $\varepsilon_k = 0$.Further expansion of equation *(18)* gives:

$$P_c(m) = \frac{1}{M}\sum_{k=0}^{M-1} E(|R_{se}(m)|^4) \\ +\frac{1}{M}\sum_{k=0}^{M-1} E(|R_{se}(m)|^2) + (E^2)^2. \tag{19}$$

As the second term of equation *(19)* is independent of the CFO as obtained in equation *(9),* we can therefore compute the gradient of $P_c(m)$ with respect to the CFO ε_k, so that the stochastic update signal may be expressed as [23]:

$$\breve{e}(m) = \frac{1}{M}\sum_{k=0}^{M-1}|R_{se}(m)|^2 \\ .\, Re\left(R_{se}{}^*(m)\frac{\partial}{\partial\varepsilon_k}R_{se}(m)\right). \tag{20}$$

and $\frac{\partial}{\partial\varepsilon_k}R_{se}(m)$ is given as:

$$\frac{\partial}{\partial\varepsilon_k}R_{se}(m) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\left(r_{se}(n).\,j\frac{2\pi n\varepsilon_k}{N}\right).\, e^{-j2\pi nk/N}. \tag{21}$$

To achieve a lower system complexity, the update error signal in equation *(20)* is simplified and the approximated stochastic update signal is therefore obtained as follows [23]:

$$\breve{e}^{appox.} = \frac{1}{M}\sum_{k=0}^{M-1}|R_{se}(m)|^2\, Re(R_{se}{}^*(m)) \\ .\big(R_{se}(m+1) - R_{se}(m-1)\big). \tag{22}$$

Therefore, the expression in equation *(22)* is used to update the carrier frequency-tracking loop and effectively combats the influence of the ICI induced in the OFDM-IDMA system by multiple simultaneous users.

3.2 The Kernel Least Mean Square Algorithm

The Kernel least mean square algorithm is simple to implement and highly efficient for prediction, estimation and correction. The modulated input data is utilized in the implementation of the Kernel function, which enhances the efficiency of the algorithm and its overall influence on the output of the system. The KLMS synchronization algorithm is achieved by executing the popular Least Mean Square (LMS) algorithm in the kernel space [25]. The update of the KLMS coefficient vector, like the conventional LMS, is obtained as follows:

$$F(n+1) = F(n) + 2\mu \times \text{ɛ̧}(n) \times \Psi\big(x_k(n)\big), \tag{23}$$

where $F(n)$ is the coefficient vector, and the mapping process is achieved by the function $\Psi\big(x_k(n)\big)$ while μ is the step-size. The error signal, which updates the frequency-tracking loop is represented by $\text{ɛ̧}(n)$, and can be expressed mathematically as:

$$\text{ɛ̧}(n) = r(n) - r_{se}(n), \tag{24}$$

where $r(n)$ is the desired signal and $r_{se}(n)$ is the received baseband signal in the presence of synchronization errors. The expected output of the OFDM-IDMA system is therefore given as [25]:

$$y(n) = \big[F(n), \Psi\big(x_k(n)\big)\big]. \tag{25}$$

Also, expressing equation *(23)* in its non-recursive form gives [26]:

$$F(n) = F(0) + 2\mu\sum_{i=0}^{N-1}\text{ɛ̧}(n)\Psi\big(x'_k(n)\big). \tag{26}$$

Initializing $F(0) = 0$, we therefore obtain $y(n)$ as derived from equations *(25)* and *(26)* as:

$$y(n) = 2\mu\sum_{i=0}^{N-1}\text{ɛ̧}(n)\big[\Psi\big(x'_k(n)\big), \Psi\big(x_k(n)\big)\big]. \tag{27}$$

Now introducing the Kernel function, the output in terms of the error signal is therefore written as:

$$y(n) = 2\mu\sum_{i=0}^{N-1}\text{ɛ̧}(n)\text{Ƙ}(\mathrm{x_k(n), x'_k(n)}). \tag{28}$$

where Ƙ denotes the Kernel function, which is given as [26]:

$$\text{Ƙ}(\mathrm{x_k(n)}, \mathrm{x'_k(n)}) = \exp(-||\mathrm{x_k(n)} - \mathrm{x'_k(n)}||^2/\omega^2), \quad (29)$$

and ω is the kernel width parameter.

However, for an enhanced system tracking and amplitude stability, the normalized KLMS (NKLMS) is presented. The NKLMS helps to stabilize the step-size parameter so that $F(n+1)$ controls better and minimizes error in the system. Thus, from (23),

$$F(n+1) = F(n) + \frac{2\mu}{[\Psi(x'_k(n)), \Psi(x_k(n))]} . \varepsilon(n) \times \Psi(x_k(n)). \quad (30)$$

Similar to (26),

$$F(n) = F(0) + 2\mu \textstyle\sum_{i=0}^{N-1} \varepsilon(n) \frac{\Psi(x'_k(n))}{[\Psi(x'_k(n)), \Psi(x_k(n))]}. \quad (31)$$

Initializing $F(0) = 0$ with no *a priori* information available [27],

$$F(n) = 2\mu \sum_{i=0}^{N-1} \varepsilon(n). \frac{\Psi(x'_k(n))}{[\Psi(x'_k(n)), \Psi(x_k(n))]}. \quad (32)$$

Thus, from (25) and (32), $y(n)$ is derived as

$$y(n) = 2\mu \sum_{i=0}^{N-1} \varepsilon(n) \frac{\Psi(x'_k(n))}{[\Psi(x'_k(n)), \Psi(x_k(n))]} . \Psi(x_k(n)). \quad (33)$$

The derivation above therefore gives the expression for the normalized KLMS. Hence, with the sufficient knowledge of the modulated signal at the receiver end of the system and the update error signal as derived, the degrading influence of the synchronization errors is effectively corrected.

4. SIMULATIONS AND DISCUSSION

Computer simulations are carried out first to demonstrate and verify the performance of the OFDM-IDMA system in the presence of carrier frequency offset errors. Then the impact of the proposed algorithms on the overall performance of the multicarrier IDMA system is validated. The computer simulations are documented based on the bit error rate performance of the OFDM-IDMA system model used. The OFDM-IDMA system model operates at a carrier frequency of 2GHz in a fading multipath channel of M= 16 paths. The QPSK modulation technique is employed, and the number of sub-carriers is set at N=128 with input data of length 32 bits. The number of sub-carriers *N* should be varied in practice, to provide each active user with variable data rates. However, we assume the same number of sub-carriers for all users in the computer simulation for convenience. Spreading length is also set to 4, with randomly generated interleavers and sampling period of 0.5μs. The performance of the OFDM-IDMA system model is demonstrated, applying the proposed synchronization algorithms, in a Rayleigh multipath channel with normalized Doppler frequencies of f_D = 0.0136, and f_D = 0.1808 corresponding to mobile speeds of v= 15 km/h, and v = 200 km/h respectively. The computer simulations are carried out with varying mobile speed to validate the performance of the proposed algorithms in both slow and fast fading multipath channels.

As stated earlier, the introduction of the OFDM process makes the OFDM-IDMA system susceptible to carrier frequency offset errors. Carrier frequency offsets attenuate the useful signal, increase the system bit error rate and degrade system performance. In Fig. 3, the bit error rate performance of the OFDM-IDMA scheme in the presence of CFOs is shown. For this simulation, CFOs values are assumed to be known based on the study in [28], where different ways to obtain carrier frequency offsets in OFDM systems are presented. CFO values are therefore varied from zero, which represents the perfect synchronization scenario, up to 0.18. The degrading effect of carrier frequency offset errors on the system model, as studied in [12, 13, 14], is observed as the value of the CFO increases. The trend of the plot depicts that further increase in carrier frequency offset values will only lead to greater degradation in the overall output of the OFDM-IDMA system.

The ideal OFDM-IDMA scenario, where there are no synchronization errors in the system at CFO=0, is included as a benchmark in the computer simulations to clearly demonstrate the impact of carrier frequency offsets on the system, as well as the subsequent influence of the proposed synchronization algorithms on the overall performance of the system model.

Fig. 4 shows the impact of the linear MMSE-based synchronization algorithm on the OFDM-IDMA system model. The algorithm is applied in the presence of high carrier frequency offsets of 0.1 and 0.18 for clear demonstration of its effectiveness. An appreciable improvement in the overall output of the system is observed, which signifies an effective reduction in the power of the ICI caused by the residual CFOs of the concurrent users in the system.

In Fig. 5, the bit error rate performance of the OFDM-IDMA system upon the application of the KLMS algorithm is shown. The proposed algorithm works in accordance with the kernel matrix, which is achieved by the implicit products of the information data samples, using the kernel function [29]. The step-size of the algorithm is set at μ = 0.5 for quick convergence [30]. At the lower CFO of 0.05, an absolute synchronization is obtained. Also, a significant system performance is observed as well, even at a higher CFO value of 0.1. The impact of this algorithm on the system model is therefore, conspicuous and highly effective.

For better comparison, the MMSE and the KLMS algorithms are shown on the same plot in Fig.6. The KLMS algorithm attains a comprehensive synchronization, better than what is obtained in the MMSE-based algorithm. The efficacy of both algorithms is also visible at a higher CFO value of 0.1, with the KLMS algorithm achieving a better system output.

Also, the impact of the KLMS and the linear MMSE algorithms on the OFDM-IDMA system model is investigated in a Rayleigh fading channel of varying mobile speeds of 15km/h and 200km/h. The efficiency of the proposed algorithms is significant and obvious in both cases, as shown in Fig. 7.

Fig. 8 shows the comparison of the KLMS algorithm shown in Fig. 6 and that of the improved normalized KLMS algorithm. The NKLMS brings stability into the system as well as an improved overall performance. As seen from the plot, the NKLMS even outperforms the regular KLMS in both cases (i.e. CFO=0.05 and CFO=0.1) although this is more visible at a higher CFO value of 0.1. Also, both algorithms are implemented at a varying mobile speed of 15km/h and 200 km/h with CFO =0.1, as shown in Fig. 9 for better comparison. From the plot, the NKLMS offers a better and improved output.

Finally, the MMSE-based algorithm, the KLMS algorithm and its normalized counterpart, are implemented and compared in Fig. 10. As discussed earlier, the plot ascertains the trend, which shows that the MMSE-based algorithm has the least impact on the system while the NKLMS exceeds the other algorithms in performance. In terms of computational complexity, the discrete-time derivative [23, 31] is employed for the MMSE-based algorithm to obtain the stochastic update signal in (22) with computational complexity of $O(N^2)$. Also, the KLMS computational complexity is of $O(N)$ [32], which ensures significant overhead is not added to the overall system complexity. The implementation of the KLMS algorithm therefore offers a better and improved BER output with lower computational complexity.

5. CONCLUSION

In light of the proven degrading impact of synchronization errors on the performance of the OFDM-IDMA system, three effective algorithms have been proposed and presented to combat this undesirable effect. The linear MMSE-based synchronization algorithm, which focuses on the reduction of the ICI power due to the residual CFOs emanating from simultaneous users, is first employed to minimize the impact of synchronization errors in the system. Furthermore, the KLMS algorithm, together with its normalized counterpart, was implemented for effective carrier frequency synchronization in the OFDM-IDMA systems. The KLMS algorithms, like the MMSE-based algorithm, was implemented in practical conditions of high carrier frequency offsets, with varying mobile speeds depicting both slow and fast fading multipath channel scenarios. Simulation results, which show the effectiveness and the significant influence of the KLMS algorithm, have been documented. It is noteworthy, however, that the NKLMS algorithm achieves the most efficient, as well as improved system performance and stability even in a varying, fast fading multipath scenario.

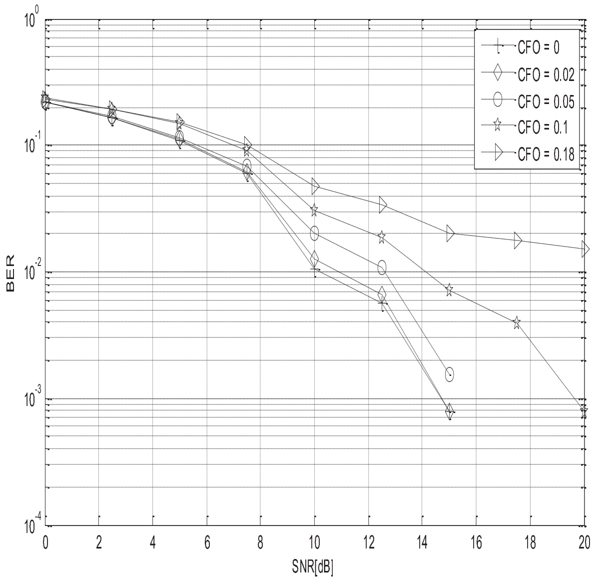

Fig. 3 The general performance of the OFDM-IDMA system model with increasing CFOs from 0 to 0.18.

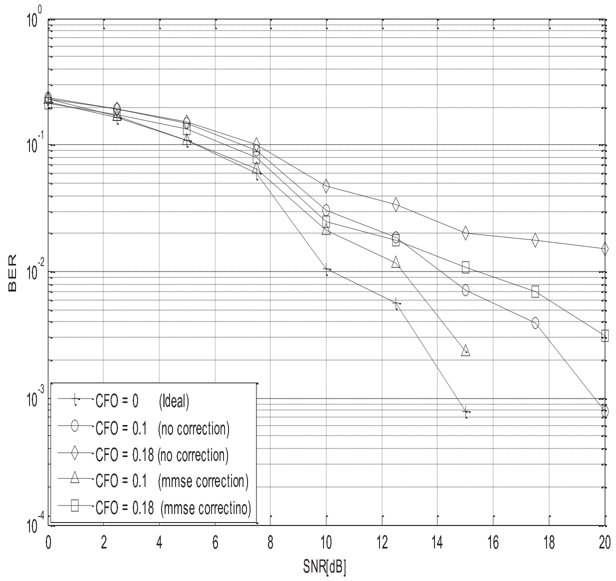

Fig. 4 The impact of the linear MMSE-based synchronization algorithm on the OFDM-IDMA system model with carrier frequency offsets 0.1 and 0.18.

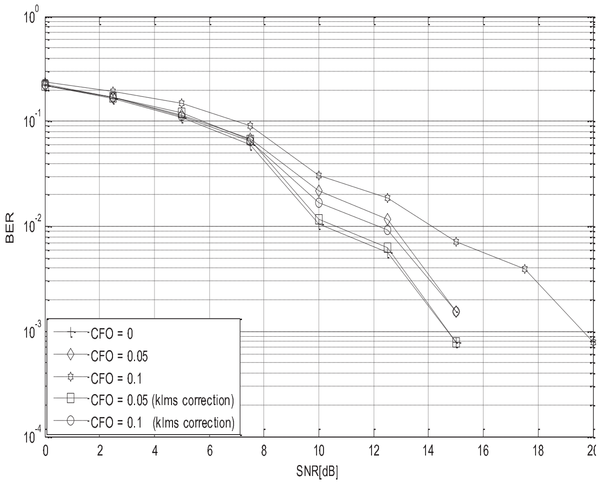

Fig. 5 The impact of the KLMS synchronization algorithm on the OFDM-IDMA system model with carrier frequency offsets 0.05 and 0.1.

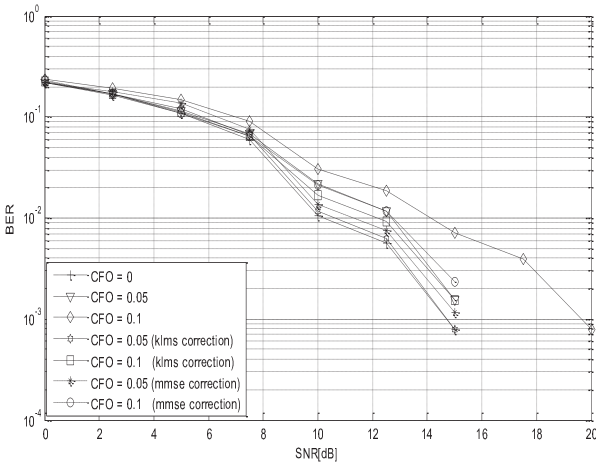

Fig. 6 The impact of the MMSE and the KLMS synchronization algorithms on the OFDM-IDMA system model with carrier frequency offsets 0.05 and 0.1.

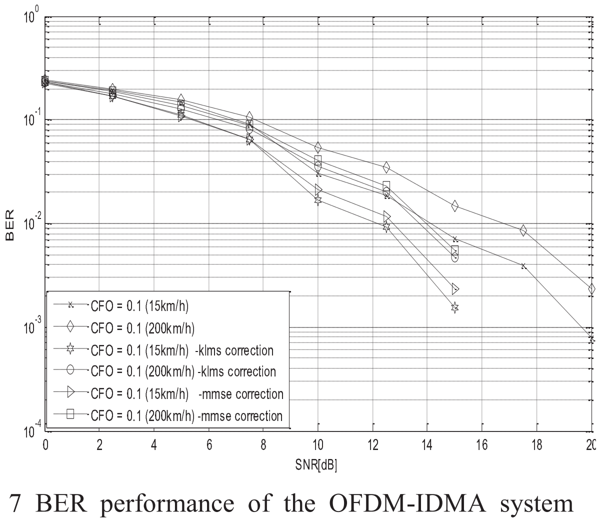

Fig. 7 BER performance of the OFDM-IDMA system model with two of the proposed algorithms in both slow and fast fading multipath channel of mobile speeds 15 km/h and 200 km/h.

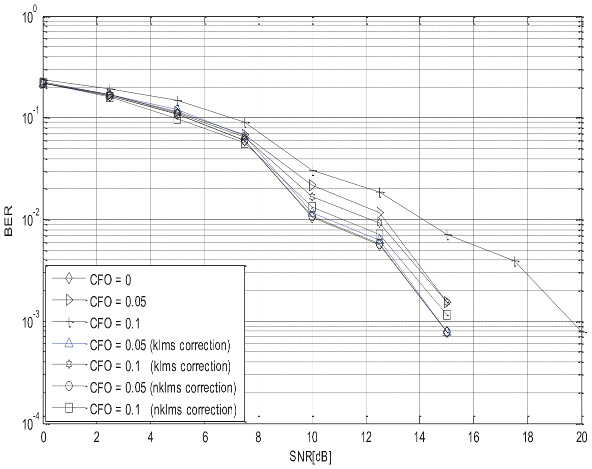

Fig. 8 Comparison of the KLMS and the NKLMS synchronization algorithms with carrier frequency offsets 0.05 and 0.1.

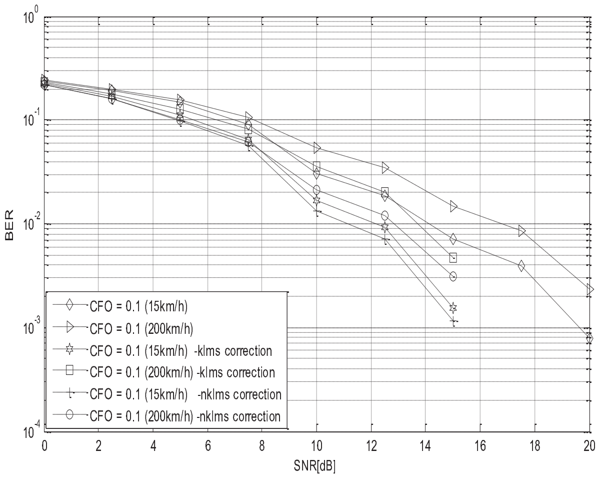

Fig. 9 Speed varying comparison of the KLMS synchronization algorithm with its normalized counterpart.

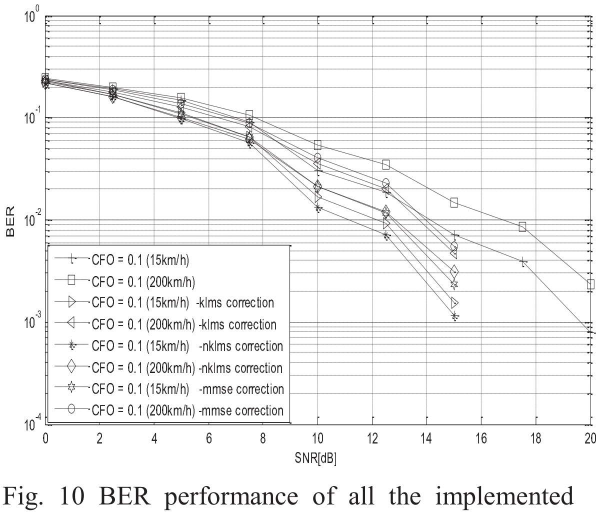

Fig. 10 BER performance of all the implemented synchronization algorithms in both slow and fast fading multipath scenario.

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