FREQUENCY SYNCHRONIZATION AND CHANNEL EQUALIZATION FOR AN OFDM-IDMA UPLINK SYSTEM

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ABSTRACT

This paper deals with a system combining orthogonal frequency division multiplexing (OFDM) and interleave-division multiple access (IDMA). OFDM makes the system robust against intersymbol interference, whereas IDMA combats the multiple access interference.
Nevertheless, two problems have to be solved: 1/ carrier frequency offset (CFO) must be estimated/corrected to guarantee the orthogonality between subcarriers. 2/ the conventional IDMA receiver requires *a priori* knowledge of the channel. Therefore, the CFO and the channel must be estimated.
Our contribution is twofold. Firstly, we suggest a sigma point Kalman filter to solve the estimation issue. In addition, we propose a new scheme where a CFO correction is no longer necessary, unlike common OFDM approaches. We show that without a CFO correction, the transmitted bits can be recovered by modifying the conventional IDMA receiver.
When considering an OFDM-IDMA network over Rayleigh fading channels, simulation results show the efficiency of the proposed algorithm.

Index Terms— OFDM, interleaved codes, frequency estimation, channel estimation, Kalman filters

1. INTRODUCTION

Today, multiple access techniques based on orthogonal frequency division multiplexing (OFDM) are the most common solutions for high-data rate multiuser transmission systems. Orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA) are used in mobile systems [1]. These techniques are robust against intersymbol interference (ISI). In addition, a multiple access interference (MAI) free transmission can be achieved by allocating different subcarriers to different users. However, the entire bandwidth in the system has to be shared by all the users, limiting the data rate.
In 2002, Ping *et al.* [2] proposed the interleave-division multiple Access (IDMA) for asynchronous spread. When using IDMA, the users do not have to be time-synchronized one another. Like code division multiple access (CDMA), the entire bandwidth resource when using IDMA can be allocated to a single user, achieving a very high single-user capacity. More specifically, the main differences between an IDMA system and CDMA system are:

1. transmitters in IDMA can be defined by a different chip-level interleaver whereas in CDMA they are defined by using different orthogonal codes;
2. to suppress the MAI, a conventional IDMA receiver uses an iterative process that combines an elementary signal estimator (ESE) and a user decoding step, whereas the CDMA receiver uses the different orthogonal codes.

Like CDMA, the multipath effects in IDMA must be suppressed and the ISI must be avoided. A solution is to use an ISI cancellation method [3]. However, its computational cost increases linearly with the number of paths and may be very high for channels with a large number of paths.
To solve this issue, Mahafeno *et al.* propose an OFDM-IDMA system [3] with a complexity independent to the number of multipaths. The authors present the receiver performances assuming that the channel is known and without considering a carrier frequency offset (CFO). However, ODFM systems are extremely sensitive to CFO. Without its estimation/correction, orthogonality between subcarriers is no longer satisfied. This leads to intercarrier interference (ICI).
CFO estimation methods for multicarrier uplink systems have been widely studied. In [4], Morelli *et al.* illustrate various schemes to estimate the CFO among different subcarrier allocation strategies. In [5], the authors propose an iterative suboptimal method based on an approximation of a maximum likelihod (ML) estimator. In addition, in [6], we present a robust frequency synchronization using a sigma point Kalman filter (SPKF) based CFO estimation. These methods only deal with OFDMA systems, where the CFO correction can be performed before or after the fast Fourier transform (FFT) step of the OFDM demodulation. However, the particular OFDM-IDMA scheme does not allow a CFO correction before the FFT step. The CFO effects of all the users in the system cannot be suppressed at the same time. Therefore, the CFO correction has to be taken into account after the FFT step.
As well in multicarrier systems, after the synchronization process, channel estimation is required. Nevertheless few papers deal with this issue for IDMA systems. In [7], an iterative channel estimation is proposed, but the authors consider a frequency synchronized system.
Given the above considerations, our contribution is twofold in this paper: 1/ To our knowledge, joint CFO/channel estimation has never been addressed in OFDM-IDMA systems. Therefore, we propose a SPKF based receiver for an OFDM-IDMA system that jointly estimates the CFO and the channel of each user in the network, by using a preamble of one OFDM-IDMA symbol. 2/ We propose a new scheme for the receiver. It operates in two steps. Firstly, the OFDM demodulation is performed without any correction over the received signal. Then, the resulting signal is inserted in a modified version of the IDMA receiver, initially proposed in [2]. Finally, taken into account the interference produced by the CFO and knowing all the CFOs and the channel state informations (CSIs), the IDMA iterative process is able to cancel both the ICI and the MAI, and to recover the sent symbols.
The paper is organized as follows: system and signal models are presented in section 2. Section 3 shows the OFDM-IDMA receiver scheme. Simulation results are presented in section 4 and conclusions are given in section 5.
In the following, $(.)^T$ denotes the transposition operation and $\mathbf{I}$ is the

identity matrix. $Re\{.\}$ and $Im\{.\}$ denote the real and the imaginary part of $\{.\}$, respectively. In addition, $\mathbb{E}(.)$ and $Var(.)$ represent the mean and the covariance of $(.)$, respectively.

2. SYSTEM DESCRIPTION

Let us consider an uplink OFDM-IDMA network consisting of a base station and U simultaneously users that transmit an information. The available bandwidth B is divided among K subcarriers.
The basic principles of an OFDM-IDMA transmitter for the uth user are shown in figure 1, where $u \in \{1, \ldots, U\}$. In the following, the subscript u is related to the uth user.
Let us now detail the OFDM-IDMA transmission: the transmitted bits are coded and spread by factor $\mathbb{S}$ in a low-rate encoder (ENC). The interleaver $\prod_u$ is applied and then the bits are modulated. Finally, the obtained IDMA symbols are:

$$\mathbf{S}_u = [S_u(0), S_u(1), \ldots, S_u(k), \ldots S_u(K-1)]^T \quad (1)$$

where $k \in \{0, \ldots K-1\}$ is the subcarrier index.
The IDMA symbols are inserted in the cyclic prefix OFDM (CP-OFDM) modulation [4]. Then, the corresponding transmitted CP-OFDM-IDMA symbol for the uth user is:

$$\mathbf{X}_u = [X_u(-N_g), \ldots, X_u(n), \ldots, X_u(K-1)]^T \quad (2)$$

where N_g is the length of the cyclic prefix (CP) and n is the time sample index.
Let us assume that the CSI of the uth user is:

$$\mathbf{h}_u = [h_u(0), h_u(1), \ldots, h_u(l), \ldots, h_u(L_u-1)]^T \quad (3)$$

where L_u is the length of the channel.
At the receiver, due to the propagation conditions, channel time-delays and CFO are induced in the signal. Time-delays between the incoming signal and the receiver can be avoided by using a sufficiently long CP between two adjacent OFDM symbols, i.e. $N_g \geq \underset{u}{max}\{L_u\}$. The signal received by the base station is a superposition of the contributions from the U active users. The received OFDM-IDMA symbol after time synchronization and the CP removal can be written as follows [4]:

$$\begin{aligned} \mathbf{R} &= \sum_{u=1}^{U} \underbrace{\mathbf{E}_u \mathbf{F}^H \mathbf{H}_u \mathbf{S}_u}_{\mathbf{R}_u} + \mathbf{B} = \sum_{u=1}^{U} \mathbf{R}_u + \mathbf{B} \quad (4) \\ &= [R(0), R(1), \ldots, R(n), \ldots, R(K-1)]^T \end{aligned}$$

where $\mathbf{R}_u = [R_u(0), \ldots, R_u(n), \ldots, R_u(K-1)]^T$, $\mathbf{F}^H$ is the inverse FFT matrix, $\mathbf{B} = [B(0), \ldots, B(K-1)]^T$ is a zero-mean complex white Gaussian noise vector with covariance matrix $\sigma_B^2 \mathbf{I}$, $\mathbf{E}_u = \text{diag}\left[1, e^{\frac{j2\pi\epsilon_u}{K}}, \ldots, e^{\frac{j2\pi(K-1)\epsilon_u}{K}}\right]$ and ϵ_u is the normalized CFO. In addition, $\mathbf{H}_u = \text{diag}\,[H_u(0), \ldots, H_u(k), \ldots, H_u(K-1)]$ is the channel frequency response matrix, where the kth diagonal element is the channel frequency response associated to the kth subcarrier, and can be expressed as:

$$H_u(k) = \frac{1}{\sqrt{K}} \sum_{l=0}^{L_u-1} h_u(l) e^{\frac{-j2\pi lk}{K}} \quad (5)$$

Let us now define the $1 \times U$ row vector that contains the normalized CFOs and the $1 \times UL_U$ row vector that contains the CSIs of each user:

$$\begin{aligned} \epsilon &= [\epsilon_1, \epsilon_2, \ldots, \epsilon_u, \ldots, \epsilon_U] \quad (6) \\ \mathbf{h} &= \left[\mathbf{h}_1{}^T, \mathbf{h}_2{}^T, \ldots, \mathbf{h}_u{}^T, \ldots, \mathbf{h}_U{}^T\right] \quad (7) \end{aligned}$$

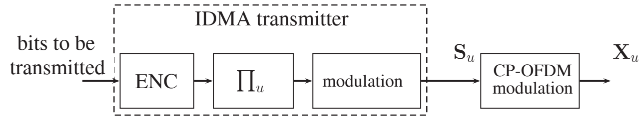

Fig. 1. OFDM-IDMA transmitter for the uth user, where ENC is the low-rate encoder, $\prod_u$ represents the interleaver, $\mathbf{S}_u$ are the IDMA symbols and $\mathbf{X}_u$ are the CP-OFDM-IDMA symbols

The nth sample of the received symbol $R(n)$ depends on (6) and (7). So, let us express the nth sample of the received OFDM-IDMA symbol as:

$$R(n) = f(n, \epsilon, \mathbf{h}) + B(n) \quad (8)$$

where $f(n, \epsilon, \mathbf{h}) = \sum_{u=1}^{U} R_u(n)$.
In the next section, the details of the proposed OFDM-IDMA receiver architecture are presented.

3. THE OFDM-IDMA RECEIVER

In this section, we present our contribution. It is the modified version of the OFDM-IDMA receiver, initially proposed by [3].
In figure 2, the conventional OFDM-IDMA uplink receiver is shown. There are two steps: 1/ OFDM demodulation which consists in removing the CP and performing an FFT. 2/ The iterative IDMA receiver which consists of an ESE and U *a posteriori* probability decoders (DECs) [2]. To estimate the bits transmitted by the uth user, let us briefly recall how the iterative IDMA receiver operates.
In the following let us denote $g_u^{\text{ESE}}(k)$ and $g_u^{\text{DEC}}(k)$ the *a priori* extrinsic logarithm likelihood ratios (LLRs) of the symbol $S_u(k)$ used by the ESE and the DEC, respectively.
Given the output $r(k)$ of the OFDM demodulation, the channel frequency response $H_u(k)$ defined in (5), the additive-noise variance σ_B^2 and $g_u^{\text{ESE}}(k)$, the ESE process generates the *a posteriori* LLRs $\mathfrak{g}_u^{\text{ESE}}(k)$ of the symbol $S_u(k)$. Then, $\mathfrak{g}_u^{\text{ESE}}(k)$ is deinterleaved to obtain the values of $g_u^{\text{DEC}}(k)$ that is inserted in the DEC. The DEC generates the *a posteriori* LLR $\mathfrak{g}_u^{\text{DEC}}(k)$, that are then interleaved to obtain the value of $g_u^{\text{ESE}}(k)$. This process is iterated several times. Once the process stops, the DECs produce hard decisions to estimate the transmitted bits [2].
The conventional OFDM-IDMA uplink receiver considers a perfectly frequency synchronized OFDM-IDMA system. However, this is a very strong assumption for a real wireless communication. In addition, the ESE requires *a priori* knowledge of the CSIs. Hence, a channel estimation is required.
As the OFDM-IDMA scheme does not allow a CFO correction before the FFT step, the FFT is performed without any CFO correction. Then the received symbol can be expressed as [4]:

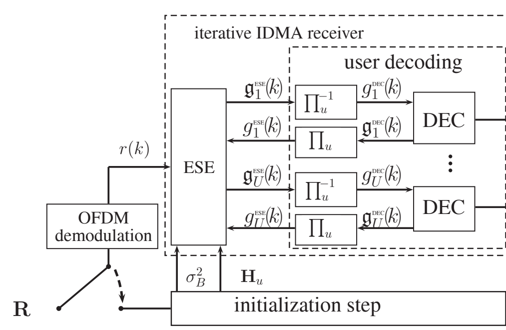

Fig. 2. Conventional OFDM-IDMA Uplink Receiver [3], where ESE is the elementary signal estimator and DEC is the *a posteriori* probability decoder

$$
\begin{aligned}
r(k) &= \sum_{u=1}^{U} H_u^{(eq)}(k) S_u(k) + ICI(\epsilon, k) + b(k) \\
&= H_u^{(eq)}(k) S_u(k) + \varsigma_u(k)
\end{aligned} \tag{9}
$$

where $\varsigma_u(k) = \sum_{u' \neq u} H_{u'}^{(eq)}(k) S_{u'}(k) + ICI(\epsilon, k) + b(k)$ is an interference term[1] and $b(k) = \frac{1}{\sqrt{K}} \sum_{n=0}^{K-1} B(n) e^{\frac{-j2\pi nk}{K}}$, $ICI(\epsilon, k)$ is the ICI[2] caused by all the CFOs with a variance σ_{ICI}^2, and

$$
\begin{aligned}
H_u^{(eq)}(k) &= \mathcal{F}(\epsilon_u) H_u(k) \\
\mathcal{F}(\epsilon_u) &= \frac{sin(\epsilon_u \pi)}{sin(\frac{\epsilon_u \pi}{K})} e^{j2\pi\epsilon_u \frac{K-1}{K}}
\end{aligned} \tag{10}
$$

It should be noted that the ICI is included in $\varsigma_u(k)$. In the following, we will show that taken into account the ICI characteristics in the IDMA receiver the transmitted bits can be recovered. In addition, it is strictly necessary to know the values of (6) and (7) at the IDMA receiver. In the next subsection, the estimation of these vectors is presented.

3.1. Multiple Joint CFO/channel Estimation

Different schemes to estimate the CFO/channel may be used, e.g. the iterative ML-based methods presented [4] and [5]. However, due to the iterative scheme, these methods may increase the computational complexity of the receiver.

In this subsection, we suggest a CFO/channel estimation by means of a SPKF [6]. A preamble of one OFDM-IDMA symbol is used to perform the estimation. We assume that the channels and the CFOs do not vary over the OFDM-IDMA symbols of the OFDM-IDMA frame.

First of all, let us define the following $(U + 2UL_U) \times 1$ state vector:

$$
\mathbf{x}(n) = \left[\begin{array}{ccc} \epsilon(n) & Re\left\{\mathbf{h}(n)\right\} & Im\left\{\mathbf{h}(n)\right\} \end{array} \right]^T \ \forall n \tag{11}
$$

that satisfies the following state equation:

$$
\mathbf{x}(n) = \mathbf{x}(n-1) \ \forall n \tag{12}
$$

Secondly, let $\mathbf{Y}(n)$ be the 2×1 observation vector that stores the real and the imaginary parts of the received signal $R(n)$:

$$
\mathbf{Y}(n) = \mathbf{A}(n, \mathbf{x}(n)) + \mathbf{V}(n) \quad \forall n \tag{13}
$$

where $\mathbf{A}(n, \mathbf{x}(n)) = \left[Re\left\{f(n, \epsilon, \mathbf{h})\right\} Im\left\{f(n, \epsilon, \mathbf{h})\right\} \right]^T$, $\mathbf{V}(n) = \left[Re\left\{B(n)\right\} Im\left\{B(n)\right\} \right]^T$ is a white Gaussian noise vector with covariance matrix $(\sigma_b^2/2)\mathbf{I}_2$.

When dealing with the non-linear state-space representation (12)-(13) of the system, methods such as the linearized recursive least squares (RLS) can be considered. More generally, if there is a model noise in (12) the extended Kalman filter (EKF) and the SPKF, namely the unscented Kalman filter (UKF) or the central difference Kalman filter (CDKF), can be used [9]. The advantages of the SPKF is that it does not require calculations of Jacobians or Hessians. The SPKF provide "accurate" estimations as long as the received signal is disturbed by a white Gaussian noise [6]. For details about the SPKF algorithm description, the reader is referred to [9].

After the time synchronization, CFOs and channels are estimated. Then, the OFDM demodulation is performed without any CFO correction and the obtained samples are used in the modified IDMA receiver presented in the next subsection.

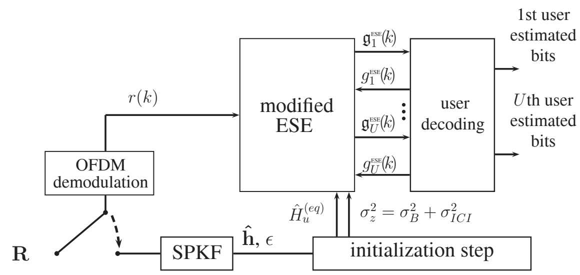

Fig. 3. Proposed OFDM-IDMA Uplink Receiver, where the user decoding is the same as in figure 2

3.2. Modified IDMA receiver

Given (4), whatever the strategy chosen by the receiver to compensate the CFO, there are still some interferences. Although the effect of the CFO for the first user or for the second can be eliminated, it cannot be suppressed for both at the same time. For this reason, our receiver does not perform any CFO correction.

After the OFDM demodulation, given (5), (10) and the estimated values of the CFO $\hat{\epsilon}_u$ and the CSI $\hat{h}_u$ we can obtain the value of $\hat{H}_u^{(eq)}(k)$, which is the estimation $H_u^{(eq)}(k)$.

Then, given the output $r(k)$ of the OFDM demodulation, the values of $\hat{H}_u^{(eq)}(k)$, the additive-noise variance σ_B^2, the ICI variance σ_{ICI}^2 and $g_u^{\text{ESE}}(k)$ the IDMA reception is performed. The proposed IDMA receiver may be applied to real and complex signals [3]. However, to simplify the explanation of the IDMA receiver let us consider a BPSK modulation. The symbol $S_u(k)$ is treated as a random variable. In the modified ESE, its mean and its covariance are computed as follows:

$$
\begin{aligned}
\mu_u(k) &= \mathbb{E}(X_u(k)) = tanh\left(\frac{g_u^{\text{ESE}}(k)}{2}\right) \quad \forall u \\
\upsilon_u(k) &= Var(X_u(k)) = 1 - (\mu_u(k))^2 \quad \forall u
\end{aligned} \tag{14}
$$

For the initialization process $g_u^{\text{ESE}}(k) = 0$ for $i = 1$, where i denotes the iteration number with $i \in \{1, \ldots, \mathcal{I}^{max}\}$. Then, assuming that $\mathbf{S}_u$ are independent and identically distributed, and applying the central limit theorem we can consider a Gaussian approximation for $\varsigma_u(k)$ and $r(k)$. Thus, they can be completely characterized by their mean and variance:

$$
\begin{aligned}
\mathbb{E}(\varsigma_u(k)) &= \mathbb{E}(r(k)) - \hat{H}_u^{(eq)}(k)\mu_u(k) \quad \forall u \\
Var(\varsigma_u(k)) &= Var(r(k)) - (\hat{H}_u^{(eq)}(k))^2 \upsilon_u(k) \quad \forall u
\end{aligned} \tag{15}
$$

where

$$
\begin{aligned}
\mathbb{E}(r(k)) &= \sum_{u=1}^{U} \hat{H}_u^{(eq)}(k)\mu_u(k) \quad \forall u \\
Var(r(k)) &= \sigma_Z^2 + \sum_{u=1}^{U} (\hat{H}_u^{(eq)}(k))^2 \upsilon_u(k) \quad \forall u
\end{aligned} \tag{16}
$$

with $\sigma_Z^2 = \sigma_{ICI}^2 + \sigma_B^2$. Unlike a conventional IDMA receiver, the distortion is now a combination of the MAI, the ICI produced by the CFOs and the Gaussian noise. The modified ESE process for the uth user at the ith iteration generates the value of the *a posteriori* LLR as follows:

$$
\mathfrak{g}_u^{\text{ESE}}(k) = 2\hat{H}_u^{(eq)}(k) \times \frac{r(k) - \mathbb{E}(\varsigma_u(k))}{Var(\varsigma_u(k))} \quad \forall u \tag{17}
$$

[1]We show in subsection 3.2, that the characteristics of the interference term $\varsigma_u(k)$ are used by the IDMA receiver to estimate the transmitted bits.

[2]The ICI can be considered as a zero-mean Gaussian vector due to the large number of subcarriers [8].

The outputs of the modified ESE are updated and used by the *a posteriori* probability DECs. Then, the outputs of the *a posteriori* probability DECs are updated to obtain the values of $g_u^{\text{ESE}}(k)$. The ESE process is again performed. Finally, the DECs produce hard decisions to obtain estimation of the transmitted bits during the final iteration $\mathcal{I}^{max}$. For details about the *a posteriori* probability DEC the reader is referred to [2].

4. SIMULATION RESULTS

We consider an OFDM-IDMA network composed of $U = 4$ users over $K = 1024$ subcarriers. The spreading factor is $\mathbb{S} = 64$. BPSK is used to modulate the information bits. The carrier frequency is at $f_c = 2.6$GHz and the channel bandwidth is set to $B = 10$MHz. We consider that the ENC consists only in the insertion of a spreading code. We define the signal-to-noise ratio as $\text{SNR} = 10\log_{10}(\frac{\sigma_s^2}{\sigma_B^2})$ and the signal-to-interference ratio $\text{SIR} = 10\log_{10}(\frac{\sigma_s^2}{\sigma_{ICI}^2})$, where $\sigma_s^2 = \mathbb{E}(|R_u(n)|^2)$. The CFOs are modeled as random variables with a normal distribution with zero-mean and variance 0.1.

We perform 1000 Monte-Carlo realizations. Figure 4 shows the CFO estimation performance in terms of minimum mean square error (MMSE) for one user in the system. The SPKF allows the CFO and the channel of the users to be estimated. The MMSE for an AWGN channel and for channels with different length are presented. Since the estimated values of the CSIs are used to perform the demodulation, we can conclude in the following that the proposed estimator gives “accurate” channel estimation.

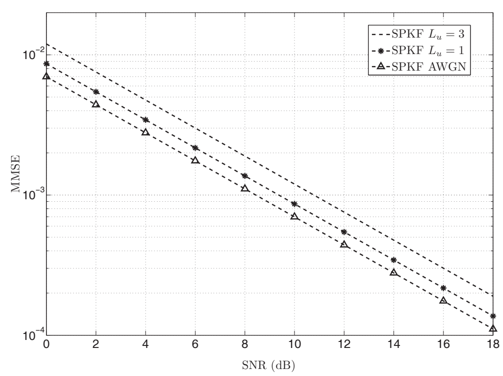

Fig. 4. CFO estimation performance in terms of MMSE, SIR$=$ 0dB.

Previous studies in [2] and [3] show the performance of the IDMA receiver for different number of multipaths, for different number of users and different number of iterations. It has been already proved that the performance of the IDMA receiver in terms of bit error rate (BER) are better when the number of multipaths and iterations increases and also when the number of users decreases. For this reason, we set the number of users to 4, and the number of iterations to 3. The following results are the average of 5000 OFDM symbols. Figure 5 shows the BER for a transmission over a normalized Rayleigh quasi-static channel composed of $L_u = 1$ and $L_u = 3\ \forall u$. The efficiency of the algorithm is confirmed. Indeed we can see that for $L_u = 1$ and a BER $= 10^{-1}$ the difference between the results of the proposed scheme and the perfect case is less than 1 dB. In addition, we can notice that for $L_u = 3$ and BER $= 10^{-2}$ between both methods is less than 1 dB. Like the results shown in [2] and [3], the performance for $L_u = 3$ are better than for $L_u = 1$. The IDMA receiver takes advantage of the diversity introduced by the propagation channel.

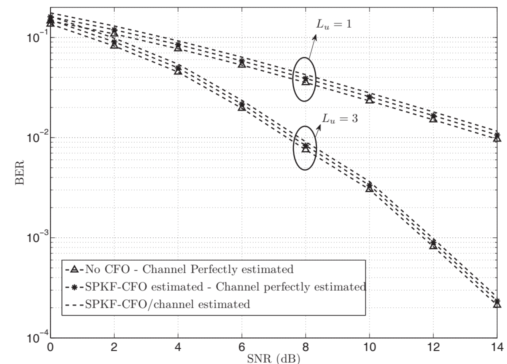

Fig. 5. BER performances for a channel L_u = 1 and L_u = 3

5. CONCLUSIONS

In this paper, a modified OFDM-IDMA receiver is proposed. The receiver is robust against time-delays due to the OFDM modulation and it is robust against the MAI due to the IDMA scheme. Unlike common approaches, the IDMA scheme also allows the CFO correction step to be skipped.

After the OFDM demodulation, the CFOs and the channels are jointly estimated by using a SPKF. Then, the OFDM demodulation is performed without any CFO correction. Finally, the modified IDMA receiver accurately estimates the transmitted bits of the uth user, by taking into account the estimations of the SPKF and the interference produced by the CFO. The proposed IDMA receiver is able to cancel the ICI produced by the the CFOs , as well as the MAI produced by the other users in the system.

Simulation results clearly show the efficiency of the proposed OFDM-IDMA receiver.

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