Universal-Filtered Multi-Carrier Technique for Wireless Systems Beyond LTE

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***Abstract*—In this paper, we propose a multi-carrier transmission scheme to overcome the problem of intercarrier interference (ICI) in orthogonal frequency division multiplexing (OFDM) systems. In the proposed scheme, called universal-filtered multi-carrier (UFMC), a filtering operation is applied to a group of consecutive subcarriers (e.g. a given allocation of a single user) in order to reduce out-of-band sidelobe levels and subsequently minimize the potential ICI between adjacent users in case of asynchronous transmissions. We consider a coordinated multi-point (CoMP) reception technique, where a number of base stations (BSs) send the received signals from user equipments (UEs) to a CoMP central unit (CCU) for joint detection and processing. We examine the impact of carrier frequency offset (CFO) on the performance of the proposed scheme and compare the results with the performance of cyclic prefix based orthogonal frequency division multiplexing (CP-OFDM) systems. We use computer experiments to illustrate the efficiency of the proposed multi-carrier scheme. The results indicate that the UFMC scheme outperforms the OFDM for both perfect and non-perfect frequency synchronization between the UEs and BSs.**

***Index Terms*—Coordinated multipoint (CoMP), orthogonal frequency division multiplexing (OFDM), carrier frequency offset (CFO), intercarrier interference (ICI), filter bank multicarrier (FBMC).**

I. INTRODUCTION

Coordinated multi-point (CoMP) communication techniques have been proposed for OFDM systems (e.g. in 3GPP LTE-Advanced standard) in order to mitigate intercell interference and improve system performance especially for cell-edge users [1]–[5]. In multi-cell wireless networks, CoMP achieves these objectives through cooperation of multiple geographically separated base stations (BSs), where the cooperation can be considered in transmission of data in downlink or reception of users' signals in uplink. Downlink COMP mainly uses joint transmission (JT) or coordinated scheduling/coordinated beamforming (CS/CB) approaches to effectively cancel the interference. Uplink CoMP performs joint reception (JR) where multiple BSs simultaneously process the received signals from user equipments (UEs) to improve the quality of detected signals [6].

One of the critical issues in CoMP-OFDM systems is their sensitivity to multiple carrier frequency offsets (CFOs) between terminals and base stations. The frequency offset can be caused by either Doppler shift resulting from terminals mobility or by oscillator frequency mismatch between a transmitter and a receiver. Multiple CFOs in CoMP-OFDM systems destroy the orthogonality between OFDM subcarriers and causes intercarrier interference (ICI) at the receiver which leads to significant system performance degradation [7]–[9]. A strong ICI happens due to high sidelobe levels of subcarrier spectrum that extend over a wide frequency band.

To overcome CFO ramifications, filter-bank based multicarrier (FBMC) technique was proposed in which prototype filters ensure a much lower side-lobe level compared to OFDM systems [10]–[12]. FBMC only becomes efficient with offset QAM (OQAM), where the real part of QAM symbols are mapped to one half of the multi-carrier symbols and the imaginary part are mapped to an interlaced half of the multi-carrier symbols. While this works well with single-cell, single user transmission, in the JR case, we obtain additional interference paths between the interlaced OQAM symbols. Furthermore, certain types of MIMO transmission (e.g. Alamouti [13]) are not supported by FBMC/OQAM. A paramount feature required in future wireless communication systems, supporting the *Internet of Things* (IoT) and *Massive Ma-*

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chine Communication (MMC), is to efficiently support transmission of small data packet [14]. A physical layer enabling this target demands efficient support of short transmission bursts. Here, FBMC/OQAM with its long filter lengths by design loses efficiency.

In this paper, we propose an alternative modulation scheme to FBMC, where a filtering operation is applied to a group of consecutive subcarriers instead of per subcarrier filtering used in FBMC. By using the proposed technique called universal-filtered multi-carrier (UFMC), the effect of sidelobe interference on the immediate adjacent subchannels can be significantly reduced. This offers better ICI robustness and better suitability for fragmented spectrum operation. Moreover, UFMC technique uses shorter filter lengths compared to OFDM cyclic prefix lengths which makes it applicable for short bursts communication. The proposed technique can be considered as a potential candidate for future wireless systems which have to support a plethora of low-cost devices to integrate the upcoming IoT and MMC. In order to serve those devices, a relaxation of the strict LTE oscillator requirements is helpful that can be achieved using our proposed scheme.

The rest of the paper is organized as follows. The system model for CoMP-OFDM is described in Section II. The proposed multicarrier technique is introduced in Section III. Section IV demonstrates the simulation results for UFMC and OFDM systems in the presence of CFO for two cases, perfect and imperfect CFO compensation. Conclusions are drawn in Section V.

Notation: Throughout this paper, we use lowercase letters to denote the time domain quantities and uppercase letters to represent signals in the frequency domain. Superscripts $(\cdot)^T$, and $(\cdot)^H$ represent transpose, and conjugate transpose, respectively. $\mathcal{C}$ represents the set of complex-valued numbers and $\mathcal{R}$ represents the set of real-valued numbers. Operator $\text{diag}\{a_1, a_2, \cdots, a_n\}$ represents a diagonal $n \times n$ matrix whose diagonal entries are $a_1, a_2, \cdots, a_n$. $\mathbf{I}_N$ represents the $N \times N$ identity matrix. Operator $\text{col}\{\cdot\}$ stacks up the matrices on top of each other.

II. CoMP-OFDM Architecture

Consider an uplink CoMP-OFDM system with K active users that simultaneously transmit their data on the same set of N_{SC} subcarriers to M separated base stations (see Fig. 1). Each base station is equipped with a single antenna and experiences multiple CFOs from K different users. In order to avoid inter-symbol interference (ISI), a cyclic prefix (CP) of N_{CP} samples are added at the beginning of each OFDM symbol. Therefore, each OFDM symbol block contains $N_B = N + N_{CP}$ samples, where N is the fast fourier transform (FFT) size. The wireless channels between users and base station are assumed to be frequency-selective with L paths which are constant over one OFDM symbol period.

The discrete-time domain received signal at the m-th BS during i-th OFDM symbol can be expressed as

$$\mathbf{y}_m^i = \sum_{k=1}^{K} \mathbf{\Omega}_r \mathbf{h}_m^k \mathbf{\Gamma}(\varepsilon_m^k) \mathbf{\Omega}_t \mathbf{V}^H \mathbf{X}_k^i + \mathbf{z}_m^i, \qquad (1)$$

where

$$\mathbf{X}_k^i = \Big[X_k^i(0),\ X_k^i(1),\ \cdots,\ X_k^i(N_{SC}-1)\Big]^T, \qquad (2)$$

$$\mathbf{\Omega}_t = \Big[[\mathbf{0}\ \mathbf{I}_{N_{CP}}]\ \mathbf{I}_{N_{SC}}\Big] \in \mathcal{R}^{N_B \times N}, \qquad (3)$$

$$\mathbf{\Gamma}(\varepsilon_m^k) = \text{diag}\Big\{1,\ e^{\frac{j2\pi\varepsilon_m^k}{N}},\ \ldots\ e^{\frac{j2\pi(N-1)\varepsilon_m^k}{N}}\Big\}, \qquad (4)$$

$$\mathbf{\Omega}_r = \Big[\mathbf{0}\ \mathbf{I}_{N_{SC}}\Big] \in \mathcal{R}^{N \times N_B}. \qquad (5)$$

In this representation, $\mathbf{X}_k^i$ is the transmitted signal from k-th user in the i-th OFDM symbol, $\mathbf{V}$ is the Fourier matrix, and $\mathbf{\Gamma}(\varepsilon_m^k) \in \mathcal{C}^{N_B \times N_B}$ is the CFO matrix. Variable $\varepsilon_m^k = \frac{f_m^k}{\triangle f}$ is the normalized CFO, where $f_m^k = f_m^{BS} - f_k^{UE}$ represents the difference of the carrier frequency between m-th BS and k-th UE and $\triangle f$ is subcarrier frequency spacing. In (1), $\mathbf{\Omega}_t$ and $\mathbf{\Omega}_r$ are the permutation matrices to add and remove cyclic prefix. Variable $\mathbf{h}_m^k$ denotes the Toeplitz channel matrix whose first column is $[h_m^k(0),\ h_m^k(1),\ \cdots,\ h_m^k(L-1),\ 0,\ \cdots,\ 0]^T$, where each $h_m^k(l)$ is a zero mean complex Gaussian random variable with variance σ_l^2. The powers of all paths are normalized such that $\sum_{l=0}^{L-1} \sigma_l^2 = 1$. In (1), $\mathbf{z}_m^i$ is the additive white Gaussian noise with entries that are independent identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance σ_n^2.

The received signal at CoMP central unit, in frequency-domain, can be expressed as (we drop the superscript i for simplicity)

$$\mathbf{Y} = \mathbf{HQX} + \mathbf{Z}, \qquad (6)$$

where

$$\mathbf{Y} = [\mathbf{Y}_1^T,\ \mathbf{Y}_2^T,\ \cdots,\ \mathbf{Y}_M^T]^T, \qquad (7)$$

$$\mathbf{Y}_m = [Y_m(0),\ Y_m(1),\ \cdots,\ Y_m(N_{SC}-1)]^T, \qquad (8)$$

$$\mathbf{H} = \text{diag}\Big\{\mathbf{H}_1,\ \mathbf{H}_2,\ \cdots,\ \mathbf{H}_M\Big\}, \qquad (9)$$

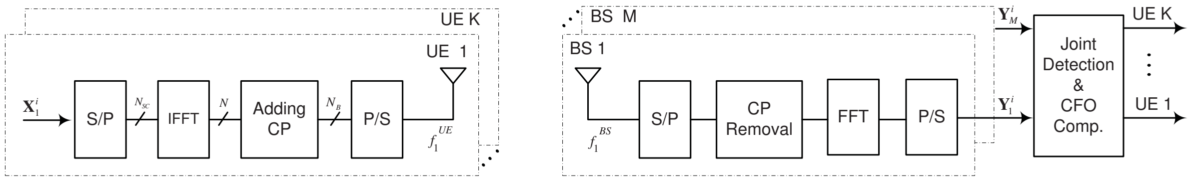

Fig. 1. System model for CoMP-OFDM in the uplink.

$$\mathbf{H}_m = \Big[\mathbf{H}_m^1,\ \mathbf{H}_m^2,\ \cdots,\ \mathbf{H}_m^K\Big], \tag{10}$$

$$\mathbf{H}_m^k = \mathrm{diag}\{H_m^k(0),\ H_m^k(1),\ \cdots,\ H_m^k(N_{SC}-1)\}, \tag{11}$$

$$\mathbf{X} = \Big[\mathbf{X}_1^T,\ \mathbf{X}_2^T,\ \cdots,\ \mathbf{X}_K^T\Big]^T \in \mathcal{C}^{KN_{SC}\times 1}, \tag{12}$$

and $\mathbf{H}$ is the channel frequency response, and the entries of $\mathbf{X}$ are defined in (2). In equation (6), $\mathbf{Q}$ is defined as

$$\mathbf{Q} = \mathrm{col}\{\mathbf{Q}_1,\ \mathbf{Q}_2,\ \ldots\ \mathbf{Q}_M\}, \tag{13}$$

where

$$\mathbf{Q}_m = \mathrm{diag}\Big\{\mathbf{Q}_m^1\ \mathbf{Q}_m^2\ \ldots\ \mathbf{Q}_m^K\Big\}, \tag{14}$$

$$\mathbf{Q}_m^k = \mathbf{V}\mathbf{\Gamma}(\varepsilon_m^k)\mathbf{V}^H, \tag{15}$$

$$\mathbf{Q}_m^k = \begin{bmatrix} q_m^k(0) & q_m^k(1) & \cdots & q_m^k(N_{SC}-1) \\ q_m^k(-1) & q_m^k(0) & \cdots & q_m^k(N_{SC}-2) \\ \vdots & \vdots & \ddots & \vdots \\ q_m^k(-N_{SC}+1) & q_m^k(-N_{SC}+2) & \cdots & q_m^k(0) \end{bmatrix}, \tag{16}$$

where

$$q_m^k(n) = \frac{1}{N_{SC}} \sum_{q=0}^{N_{SC}-1} \exp\Big(\frac{j2\pi q(\varepsilon_m^k + n)}{N_{SC}}\Big). \tag{17}$$

This is a geometric series that can be further simplified as [15]

$$q_m^k(n) = \frac{\sin\pi(\varepsilon_m^k + n)}{N_{SC}\sin\frac{\pi}{N_{SC}}(\varepsilon_m^k + n)} e^{j\pi(1-\frac{1}{N_{SC}-1})(\varepsilon_m^k+n)} \tag{18}$$

III. CoMP-UFMC Architecture

In this section, we present the proposed UFMC transmission scheme. This scheme is developed based on the principle of frequency division multiplexing (FDM) in which we divide the input data stream into several lower rate sub-streams. The block diagram of a system employing UFMC is depicted in Fig. 2. As shown in this figure, the data stream of the k-th user $\mathbf{X}_k^i$ is divided into N_{RB} sub-streams denoted by $\mathbf{X}_{k,p}^i \in \mathcal{C}^{N_{SC}^{RB}}$, for $p \in \{1, 2, \cdots, N_{RB}\}$[1]. Then, we use a pulse shaping filter with smooth edges on each resource block in time domain that leads to substantial reduction in out-of-band leakage in frequency domain. In this way, we minimize the harmful interference from adjacent subchannels of the neighboring resource block. In Fig. 3, we illustrate the power spectrum of UFMC and OFDM signals in frequency domain. In this experiment, we use a finite impulse response (FIR) chebyshev filter. Fig. 3 (a) shows the UFMC spectrum for $N_{RB} = 6$ where each RB contains 12 subcarriers. In Fig. 3 (b), we compare the power spectrum of one RB of UFMC with that of the OFDM. As it can be observed in (b), OFDM spectrum has high sidelobe levels resulted from the rectangular pulse in time domain. This causes severe ICI and performance degradation, if the orthogonality between subcarriers collapses (e.g. by CFO). As opposed to OFDM, UFMC offers a frequency well-localized pulse shaping. In addition, the proposed UFMC offers a higher spectral efficiency in comparison to OFDM, since it does not require cyclic prefix.

The time domain received signal in CoMP-UFMC system can be expressed as

$$\mathbf{y}_m^i = \sum_{k=1}^{K} \mathbf{h}_m^k \mathbf{\Gamma}(\varepsilon_m^k)\widetilde{\mathbf{F}}^H\widetilde{\mathbf{V}}^H\mathbf{X}_k^i + \mathbf{z}_m^i, \tag{19}$$

where

$$\mathbf{X}_k^i = \Big[\mathbf{X}_{k,1}^{i^T},\ \mathbf{X}_{k,2}^{i^T},\ \cdots,\ \mathbf{X}_{k,N_{RB}}^{i^T}\Big]^T \in \mathcal{C}^{N_{SC}\times 1}, \tag{20}$$

$$\mathbf{X}_{k,p}^i = \Big[X_{k,p}^i(0),\ X_{k,p}^i(1),\ \cdots,\ X_{k,p}^i(N_{SC}^{RB}-1)\Big]^T, \tag{21}$$

$$\widetilde{\mathbf{V}}^H = \mathrm{diag}\Big\{\mathbf{V}_1,\ \mathbf{V}_2,\ \cdots,\ \mathbf{V}_{N_{RB}}\Big\}, \tag{22}$$

$$\widetilde{\mathbf{F}}^H = \Big[\mathbf{F}_1,\ \mathbf{F}_2,\ \cdots,\ \mathbf{F}_{N_{RB}}\Big]. \tag{23}$$

[1]In the LTE systems, each N_{SC}^{RB} consecutive subcarriers in frequency domain is called a resource block (RB) [16].

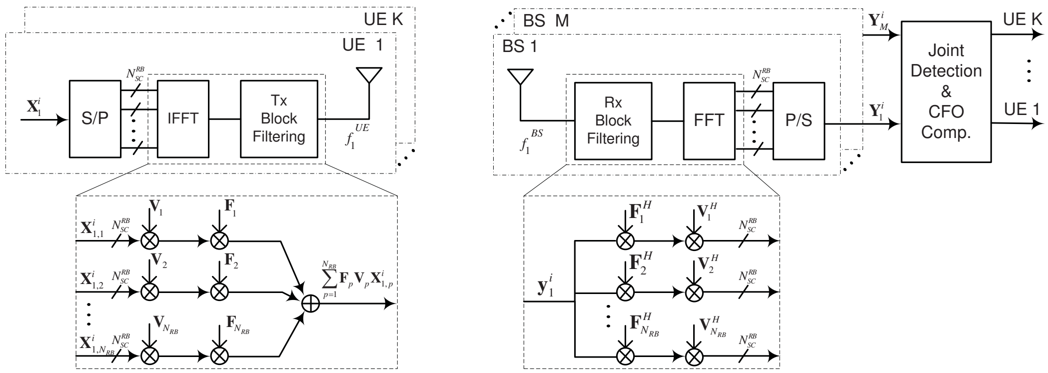

Fig. 2. System model for CoMP-UFMC in the uplink.

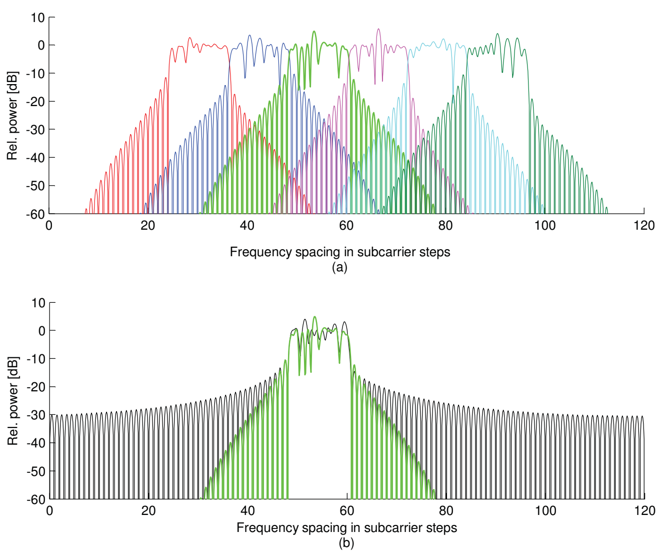

Fig. 3. (a) Superimposed spectrum of 6 different UFMC resource blocks with 12 subcarriers each, carrying random QPSK data symbols. (b) Comparison of one OFDM resource block with a UFMC resource block.

and $\mathbf{X}_{k,p}$ is the p-th sub-stream transmitted from the k-th user in the i-th OFDM symbol, and $\tilde{\mathbf{V}}^H$ is the Fourier matrix. In (22), $\mathbf{V}_p \in \mathcal{C}^{N_{SC}\times N_{SC}^{RB}}$ consists of N_{SC}^{RB} columns of Fourier matrix $\mathbf{V}$, starting from column $(p-1)N_{SC}^{RB}+1$. Variable $\tilde{\mathbf{F}}^H$ is the filter matrix, where its entry $\mathbf{F}_p$ is the Toeplitz matrix whose first column is $[b_p(0),\ \ b_p(1),\ \ \cdots,\ \ b_p(L_{FIR}-1),\ \ 0,\ \ \cdots,\ \ 0]^T$. The coefficients $b_p(j)$ for $j \in \{0,1,\cdots,L_{FIR}-1\}$ are the p-th resource block FIR filter coefficients. Moreover, per-block filter coefficients are chosen such that $\sum_{j=0}^{L_{FIR}-1}|b_p(j)|^2 = 1$.

The frequency domain received signal at all BSs can be written as (for simplicity, the superscript i is dropped in the following expressions)

$$\mathbf{Y} = \mathbf{H}\widetilde{\mathbf{Q}}\mathbf{X} + \mathbf{Z}, \tag{24}$$

where matrix $\widetilde{\mathbf{Q}}$ can be expressed as

$$\widetilde{\mathbf{Q}} = \mathrm{col}\{\widetilde{\mathbf{Q}}_1,\ \widetilde{\mathbf{Q}}_2,\ \ldots\ \widetilde{\mathbf{Q}}_M\}, \tag{25}$$

where

$$\widetilde{\mathbf{Q}}_m = \mathrm{diag}\left\{\widetilde{\mathbf{Q}}_m^1\ \widetilde{\mathbf{Q}}_m^2\ \ldots\ \widetilde{\mathbf{Q}}_m^K\right\}, \tag{26}$$

$$\widetilde{\mathbf{Q}}_m^k = \widetilde{\mathbf{V}}\widetilde{\mathbf{F}}\mathbf{\Gamma}(\varepsilon_m^k)\widetilde{\mathbf{F}}^H\widetilde{\mathbf{V}}^H. \tag{27}$$

At the CoMP central unit, the zero-forcing (ZF) linear equalizer is used to detect the transmitted signals, performing multi-antenna combining across the subcarriers, which suppresses ICI and multi-user interference. To do so, the received signal vector is multiplied with a filter matrix that can be computed as

$$\mathbf{G}_{ZF} = (\mathbf{H}_{eff}^H\mathbf{H}_{eff})^{-1}\mathbf{H}_{eff}^H, \tag{28}$$

where $\mathbf{H}_{eff} = \mathbf{H}\widetilde{\mathbf{Q}}$ for UFMC and $\mathbf{H}_{eff} = \mathbf{HQ}$ for OFDM systems.

IV. Simulation Results

In this section, we examine the performance of the proposed CoMP-UFMC system and compare the results with that of the CoMP-OFDM system. We also investigate the effect of frequency offset between BSs and UEs on the performance of both systems. Moreover, we study the impact of CFO estimation error on the symbol error rate (SER) performance of the systems. Monte-Carlo simulations are used to evaluate the SER of the proposed system.

We carry out the simulations for $L = 16$, $M = 2$, $K = 2$, $N_{SC} = 72$, $N_{RB} = 6$, $N_{SC}^{RB} = 12$, and FFT

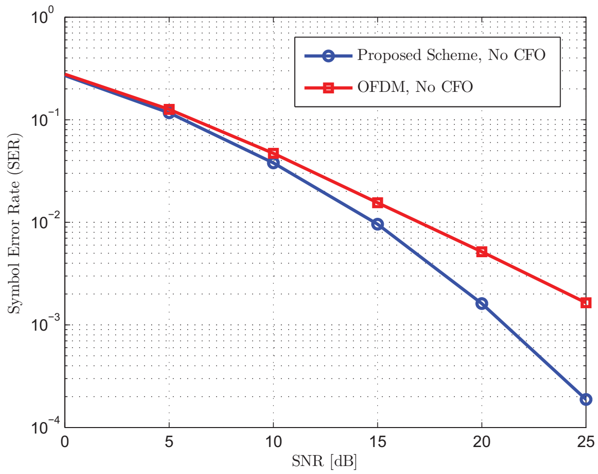

Fig. 4. SER performances of CoMP-UFMC and CoMP-OFDM systems with no CFO.

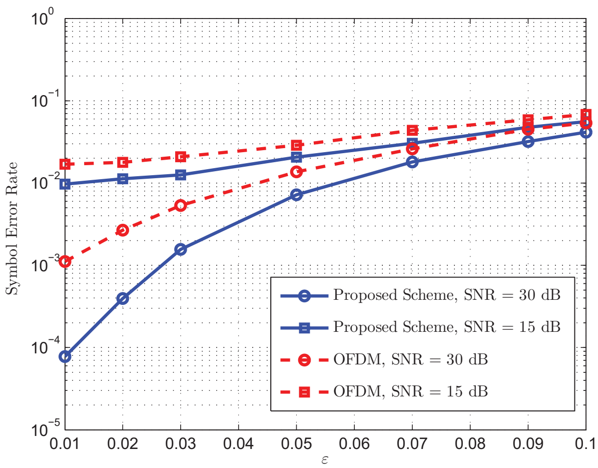

Fig. 5. SER performances of CoMP-UFMC and CoMP-OFDM systems for different CFO values.

size of $N = 128$. We assume that the symbols are chosen from a QPSK constellation with average symbol power of one. To recover the inputs signals at the receiver, linear zero-forcing (ZF) equalizer is applied. To make a fair comparison between UFMC and CP-OFDM systems, the filter length (L_{FIR}) is set to the CP length ($L_{FIR} = N_{CP} = 16$). For the UFMC scheme, we use a Chebyshev window with 120 dB stop-band attenuation where its center frequency is set at the middle of the resource block.

Fig. 4 shows the symbol error rate (SER) of UFMC and OFDM systems versus SNR in no CFO scenario (BSs and UEs are all synchronized). As shown in this figure, the proposed scheme outperforms the OFDM systems. UFMC scheme provides higher spectral efficiency compare to OFDM due to the absence of cyclic prefix samples which has to be discarded at the receiver.

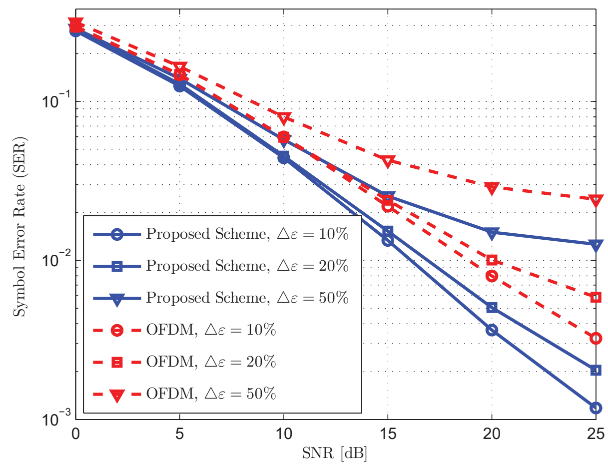

Fig. 6. SER performances of CoMP-UFMC and CoMP-OFDM systems for different CFO estimation errors.

For the results presented in Fig. 5 and Fig. 6, we presume that each UE is synchronized with its own serving BS ($\varepsilon_m^k = 0$ if $m = k$).

Fig. 5 depicts the effect of CFO on the performance of the UFMC scheme in comparison with that of the OFDM system. In this experiment, the results are obtained for two different SNR values without CFO compensation. For both techniques, the SER performance degrades as the CFO increases. This happens due to having stronger ICI.

Fig. 6 shows the SER performance of the proposed scheme and the OFDM systems in the presence of the CFO estimation error. In this figure, $\triangle\varepsilon$ denotes the CFO estimation error value that is a percentage of the CFO. In this experiment, the CFO is chosen to be 0.1. From this results, we observe that the CFO estimation error severely degrades the SER performance of the system. For instance, as shown in the figure, by increasing the CFO estimation error from 10% to 50%, the SER increases from 10^{-3} to 10^{-2} at SNR = 25 dB. The proposed scheme with $\triangle\varepsilon = 20\%$ CFO estimation error works better than the OFDM system with $\triangle\varepsilon = 10\%$ CFO estimation error.

As it is evident from the results, the performance gain increases in higher SNR (> 15 dB) as in this range the ICI becomes more noticeable. Note that in a CoMP system, the inter-cell interference is explicitly handled by the coordination, so an SNR > 15 dB is no uncommon setting in an interference-limited deployment, as happening in typical urban deployment scenarios. Thus, the SNR ranges where UFMC shows stronger gains over OFDM, according to the simulation results, are very relevant for CoMP.

V. Conclusions

In this paper, we proposed a multi-carrier transmission scheme in order to overcome the ICI problem and improve the system performance. In the proposed scheme, called UFMC, a filtering operation is applied to a group of consecutive subcarriers (e.g. a given allocation of a single user) in order to reduce out-of-band sidelobe levels that results in a better ICI robustness and better suitability for fragmented spectrum operation compared to OFDM. We showed that the UFMC outperforms the CP-OFDM for both perfect and non-perfect frequency synchronization between the UEs and BSs. We also studied the effect of imperfect CFO compensation on the SER performance of the UFMC system and compare it with that of the CP-OFDM system. The results indicate that the proposed UFMC-scheme can be a promising candidate for future 5G wireless systems. Future work will deal with optimizing the UFMC filters.

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