FBMC/OQAM for the Asynchronous Multi-User MIMO Uplink

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***Abstract*—In this paper, we evaluate the performance of filter bank-based multi-carrier with offset quadrature amplitude modulation (FBMC/OQAM) for the multi-user multiple-input multiple-output (MIMO) uplink in the presence of timing and frequency misalignments. In such a scenario, multiple access is achieved by assigning groups of sub-carriers to user nodes. The nodes are equipped with multiple antennas, and different frequency selective channel models are considered. In addition, a comparison with orthogonal frequency division multiplexing with the cyclic prefix insertion (CP-OFDM) as the currently widely used multi-carrier scheme is presented. The greater robustness of FBMC/OQAM against a lack of synchronization in the time and the frequency domain compared to CP-OFDM is shown via extensive numerical results.**

I. Introduction

Regarded as a promising alternative multi-carrier scheme to orthogonal frequency division multiplexing with the cyclic prefix insertion (CP-OFDM), filter bank-based multi-carrier modulation (FB-MC) has recently received great research attention. By adopting spectrally well-contained synthesis and analysis filter banks in the transmultiplexer configuration [1], [2], FB-MC reduces the sidelobes and avoids a high level of out-of-band radiation which CP-OFDM suffers from. Moreover, the insertion of a CP is not required in systems employing filter bank-based multi-carrier with offset quadrature amplitude modulation (FBMC/OQAM), leading to a higher spectral efficiency compared to CP-OFDM-based systems. These advantages of FB-MC gives rise to its potential applications in, for instance, cognitive radio and professional mobile radio (PMR) networks, where an effective utilization of the available fragmented spectrum is needed [3].

In multi-user multiple-input multiple-output (MIMO) uplink transmissions, perfect synchronization in the time domain and the frequency domain can hardly be guaranteed. It is generally known that CP-OFDM fails to provide a satisfactory performance in such scenarios, since the timing and frequency misalignments result in a loss of orthogonality between the sub-carriers and lead to multiple access interference as well. To resolve these problems, timing offset and frequency offset compensation techniques may be employed, and interference cancellation algorithms may also be incorporated to further alleviate the performance degradation. However, these methods unavoidably induce a heavier computational burden and may require additional information exchange which decreases the spectral efficiency. On the other hand, the FB-MC scheme features a well-localized spectrum and is more robust against asynchronism compared to CP-OFDM. In [4], it is numerically shown that FBMC/OQAM-based systems are less sensitive to synchronization errors in uplink transmissions than CP-OFDM systems considering single-antenna user nodes and additive white Gaussian noise (AWGN) channels. Moreover, the authors of [5] arrive at the conclusion that FBMC/OQAM-based systems are more robust against carrier frequency offsets compared to CP-OFDM on the uplink of multiple access networks with single antenna user nodes.

In this work, our focus is also on FB-MC-based systems that employ FBMC/OQAM. Here the real and imaginary parts of each complex-valued data symbol are staggered by half of the symbol period [1]. Therefore, the desired signal and the intrinsic interference caused by symbols transmitted on adjacent sub-carriers and time instants are separated in the real domain and the pure imaginary domain, respectively [6]. We consider a multi-user uplink scenario in the presence of symbol timing offsets or residual carrier frequency offsets, and the user nodes are assigned different groups of sub-carriers to achieve the multiple access. All nodes are equipped with multiple antennas, and different frequency selective channel models are considered. Linear MMSE receiver-based processing is employed at the access point (AP) to recover signals from each user node. Comparative performance evaluations of FBMC/OQAM and CP-OFDM are carried out. Extensive simulation results demonstrate that FBMC/OQAM systems are more robust against timing and frequency misalignments in contrast to CP-OFDM systems.

The remainder of the paper is organized as follows. Section II presents an overview of multi-user MIMO uplink transmissions, and the data model is given taking into account the presence of symbol timing offset or the effects of residual carrier frequency offsets. Moreover, the difference between FBMC/OQAM and CP-OFDM is discussed. In Section III, we further describe the receive processing technique that is employed in this work. Numerical experiments and results are presented in Section IV, before conclusions are drawn in Section V.

II. Scenario description and data model

We consider a multi-carrier uplink multiple access scenario, where U users each assigned a group of sub-carriers transmit signals to a single AP simultaneously. The AP is equipped with Q receive antennas, and the u-th user node has P_u transmit antennas, $u = 1, 2, \ldots, U$. The transmitted signals from each user suffer from frequency selective fading characteristics of

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multi-path channels. A block-wise fashion of the sub-carrier allocation is adopted. In Fig. 1, we illustrate an example for the two-user case. User 1 occupies the sub-carriers with indices $k = 0, 1, \ldots, M_1 - 1$, and User 2 transmits on the sub-carriers with indices $k = M_1 + G, \ldots, M_1 + M_2 + G - 1$, where M_u denotes the number of sub-carriers allocated to the u-th user, and G represents the number of sub-carriers as the guard band. In case of more than two users, the sub-carrier allocation can be similarly defined except for the fact that multiple guard bands are employed such that adjacent sub-carrier blocks are separated.

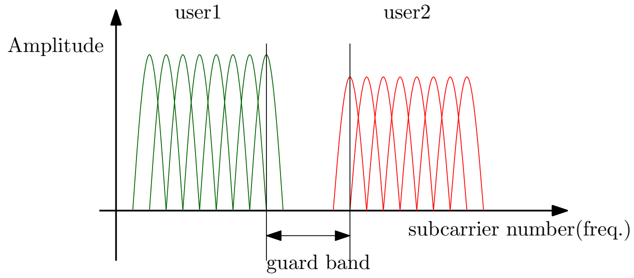

Fig. 1. Illustration of the block-wise sub-carrier allocation for the two-user case

In the following subsections, the data model of the multi-user MIMO uplink is given where the symbol timing offsets and residual carrier frequency offsets are taken into account. The difference between an FBMC/OQAM-based system and a CP-OFDM-based system is also pointed out and reflected in the introduction of the data model.

A. Symbol timing offsets

In the presence of symbol timing offset, the received signal at the q-th receive antenna of the AP, where $q = 1, 2, \ldots, Q$, can be expressed as

$$r_q(t) = \sum_{u=1}^{U} \sum_{p=1}^{P_u} h_{pq}^{(u)}(t) * s_p^{(u)}(t - \Delta t_u) + n_q(t), \quad (1)$$

where $*$ denotes the convolution operation, and $h_{pq}^{(u)}(t)$ means the frequency selective channel impulse response on the link between the p-th transmit antenna of the u-th user and the q-th receive antenna of the AP. At each user node, full multiplexing is considered, i.e., the number of data streams transmitted by the u-th user equals the number of transmit antennas P_u. The multi-carrier signal transmitted at the p-th antenna of the u-th user is denoted by $s_p^{(u)}(t)$, and it is obtained by either a CP-OFDM/QAM modulator or an FMBC/OQAM modulator as introduced in Section II-C. Moreover, we use Δt_u to denote the symbol timing offset of the u-th user. The noise term $n_q(t)$ is modeled as a circular symmetric complex Gaussian process with zero mean, and the noise power spectral density is denoted by N_0.

Employing a multi-carrier modulation scheme and allowing users to transmit on different sub-carrier groups contribute to the orthogonality between the transmissions on different sub-carriers and an isolation of different users. Nevertheless, as it is very difficult to ensure that the signals from different users arrive at the AP simultaneously, the exact symbol-timing is not usually sufficiently warranted. This may heavily degrade the performance due to the adjacent channel interference resulting from the loss of the orthogonality.

B. Residual carrier frequency offsets

In this paper we define the normalized carrier frequency offset as the ratio of the frequency mismatch and the sub-carrier spacing. Thereby, the received signal at the q-th receive antenna of the AP, where $q = 1, 2, \ldots, Q$, in the presence of carrier frequency offsets is written as

$$r_q(t) = \sum_{u=1}^{U} e^{j\frac{2\pi\eta_u t}{T}} \sum_{p=1}^{P_u} h_{pq}^{(u)}(t) * s_p^{(u)}(t) + n_q(t), \quad (2)$$

where T denotes the symbol duration, and η_u is the normalized carrier frequency offset of the u-th user. Here perfect synchronization in the time domain is assumed.

Multi-carrier systems carry information data on frequency orthogonal sub-carriers for parallel transmissions to combat the distortion caused by frequency selective fading channels. However, for practical implementations, the orthogonality between sub-carriers is not guaranteed due to frequency synchronization errors. Consequently, the performance might be significantly degraded. Note that carrier frequency offsets can be estimated by using training symbols in both CP-OFDM and FBMC/OQAM-based transmissions. For instance, a maximum likelihood estimator in the frequency domain was investigated in [7], and it helps in compensating carrier frequency offsets caused by phase noise, Doppler frequency shift and physical limitations of oscillators. However, a perfect estimation of the carrier frequency offset is still unavailable, and the residual carrier frequency offsets remain.

C. Multi-carrier modulation by using FBMC/OQAM and CP-OFDM

For simplicity of notation, we ignore the user index u and the data stream index p, and the CP-OFDM modulated symbol is given as

$$s(t) = \sum_{k=0}^{M-1} S(k) e^{j2\pi f_k t}, \quad (3)$$

where $S(k)$ denotes the narrowband QAM symbol transmitted on the k-th subcarrier, f_k represents the corresponding carrier frequency, and M is the number of sub-carriers. Each sub-carrier component of a CP-OFDM symbol with the effective duration of T_{sym} (including the duration of the CP) can be considered as a narrowband signal within a rectangular sampling window of length T_{sym}. The rectangular window leads to a sinc function in the frequency domain. In CP-OFDM systems, the power spectrum of a set of these frequency separated sinc functions produces out-of-band power. If the user nodes are not perfectly synchronized, significant interference will be picked up by adjacent sub-channels. A guard band in the frequency domain can be inserted between the sub-channels to reduce the effect of channel interference at the price of a further loss of spectral efficiency.

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In case of FBMC/OQAM systems, OQAM is employed and the transmitter builds the signal as [1]

$$\begin{aligned} s(t) = \sum_{k=0}^{M/2-1} \sum_{n} \Big(&\Re\{S(2k)\}g(t-nT)+ \\ &j\Im\{S(2k)\}g(t-nT-\frac{T}{2})\Big)e^{j2\pi(2k)f_{2k}t}+ \\ &\Big(\Re\{S(2k+1)\}g(t-nT-\frac{T}{2})+ \\ &j\Im\{S(2k+1)\}g(t-nT)\Big)e^{j2\pi(2k+1)f_{2k+1}t}, \end{aligned} \tag{4}$$

where n is the tap index of the pulse shaping filter $g(t)$. The items $\Re\{S(k)\}$ and $\Im\{S(k)\}$ denote the real and imaginary parts of the QAM complex-valued symbols, respectively. The in-phase and quadrature components of the QAM signal have a time offset of half a symbol period. A set of spectrally well contained synthesis and analysis filter banks is considered in the FBMC/OQAM transmission systems. One of the common approaches is to use modulated uniform polyphase filter banks based on prototype filter design, and the system spectral characteristics are determined by the prototype filter. By employing FBMC/OQAM, the side lobes of the multi-carrier components can be significantly reduced [8], and the insertion of a CP is not required.

III. Receive processing

At the AP, assuming that the signals from the U users are perfectly separated, receive processing techniques for point-to-point MIMO FBMC/OQAM systems can be employed. Considering that the channel on each sub-carrier can be treated as flat fading, the received signal on the k-th sub-carrier and at the n-th time instant from the u-th user is written as follows

$$\begin{aligned} \boldsymbol{y}_k^{(u)}[n] =& \boldsymbol{H}_k^{(u)}[n]\boldsymbol{d}_k^{(u)}[n] + \sum_{i=n-3}^{n+3}\sum_{\ell=k-1}^{k+1} \boldsymbol{H}_\ell^{(u)}[i]c_{i\ell}\boldsymbol{d}_\ell^{(u)}[i] \\ &+ \boldsymbol{n}_k^{(u)}[n], \quad (\ell,i)\neq(k,n), \end{aligned} \tag{5}$$

where $\boldsymbol{d}_k^{(u)}[n] \in \mathbb{R}^{P_u}$ is the desired signal from the u-th user on the k-th sub-carrier and at the n-th time instant when $(k+n)$ is even[1]. The terms $c_{i\ell}\boldsymbol{d}_\ell^{(u)}[i]$ contribute to the intrinsic interference and are pure imaginary, where $\ell = k-1, k, k+1$, $i = n-3, \ldots, n+3$, and $(\ell, i) \neq (k, n)$. The coefficients $c_{i\ell}$ represent the system impulse response determined by the synthesis and analysis filters. The PHYDYAS prototype filter [8] is used, and the overlapping factor is chosen to be $K = 4$. For more details about FBMC/OQAM systems, the reader is referred to [9]. Here $\boldsymbol{H}_k^{(u)}[n] \in \mathbb{C}^{Q\times P_u}$ contains the frequency responses of the channels between each transmit antenna of the u-th user and each receive antenna of the AP, and $\boldsymbol{n}_k^{(u)}[n]$ denotes the additive white Gaussian noise vector with variance σ_n^2.

In several publications on MIMO FBMC/OQAM systems, such as [10] and [11], it is assumed that the channels on adjacent sub-carriers are almost the same. The received signal on the k-th sub-carrier and at the n-th time instant from the u-th user can be accordingly written as

$$\boldsymbol{y}_k^{(u)}[n] = \boldsymbol{H}_k^{(u)}[n]\widetilde{\boldsymbol{d}}_k^{(u)}[n] + \boldsymbol{n}_k^{(u)}[n], \tag{6}$$

where $\widetilde{\boldsymbol{d}}_k^{(u)}[n]$ contains the real-valued desired signal and the pure imaginary interference

$$\widetilde{\boldsymbol{d}}_k^{(u)}[n] = \boldsymbol{d}_k^{(u)}[n] + \sum_{i=n-3}^{n+3}\sum_{\ell=k-1}^{k+1} c_{i\ell}\boldsymbol{d}_\ell^{(u)}[i], \quad (\ell,i)\neq(k,n). \tag{7}$$

Considering $\widetilde{\boldsymbol{d}}_k^{(u)}[n]$ as an equivalent transmitted signal, (6) resembles the data model of a MIMO CP-OFDM system. Consequently, transmission strategies that have been developed for MIMO CP-OFDM systems can be straightforwardly extended to MIMO FBMC/OQAM systems where only one additional step is required, i.e., taking the real part of the resulting signal. In this work, a linear MMSE receiver is employed, and the recovered desired signal from the u-th user is then obtained as

$$\hat{\boldsymbol{d}}_k^{(u)}[n] = \Re\left\{\boldsymbol{W}_k^{\mathrm{H}}[n]\boldsymbol{y}_k^{(u)}[n]\right\}, \tag{8}$$

where $\boldsymbol{W}_k[n] \in \mathbb{C}^{Q\times P_u}$.

It is worth noting that the two-step receiver proposed in [11] can also be applied to further enhance the performance. By combining linear processing and widely linear processing, the two-step receiver exploits the non-circularity of the signals of an FBMC/OQAM system.

IV. Simulation results

In this section, we present numerical results with respect to the comparison between CP-OFDM and FBMC/OQAM in asynchronous multi-user MIMO uplink settings. The multi-carrier scheme-related parameters are set according to those for LTE 5 MHz transmissions. The sub-carrier spacing is 15 kHz, and the FFT size is 512. Here the CP length for CP-OFDM is set to $T/8$. In case of FBMC/OQAM, the PHYDYAS prototype filter [8] is used, and the overlapping factor is chosen as $K = 4$. In all examples, we employ the linear MMSE-based receive processing that is described in detail in Section III.

A. Uplink transmissions with symbol timing offsets

First, we consider a 2-user scenario where the two users and the base station are each equipped with two antennas. A block-wise sub-carrier allocation scheme as illustrated in Fig. 1 is adopted. The ITU Pedestrian-A channel model [12] is used in the simulations. Assuming perfect synchronization in the time domain and in the frequency domain, we present the bit error rate (BER) performances of CP-OFDM and FBMC/OQAM in Fig. 2. Note that the SNR here represents E_b/N_0. It can be observed that when no guard band is employed, the performance of FBMC/OQAM becomes worse than that of CP-OFDM in the high SNR regime. The reason is that without a guard band the last sub-carrier of the first user is interfered by the transmission of its adjacent sub-carrier which belongs to the second user and experiences a different channel, while in the receive processing presented in Section III the channel is treated as the same for the desired symbol on

[1]For the case where $(k+n)$ is odd, the desired signal on the k-th sub-carrier and at the n-th time instant is pure imaginary, while intrinsic interference is real. As the two cases are essentially equivalent to each other, we only take the case where $(k+n)$ is even to describe the receive processing employed in this paper.

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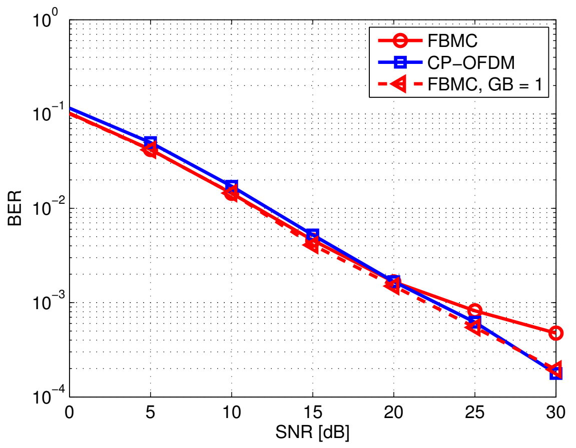

Fig. 2. Comparison between FBMC/OQAM and CP-OFDM for a 2-user uplink scenario considering perfect synchronization in the time domain and in the frequency domain (GB - guard band in the number of sub-carriers)

each sub-carrier and the intrinsic interference. It also applies to the detection of the signal on the first sub-carrier of the second user. This fact results in the performance degradation of FBMC/OQAM. On the other hand, when employing one sub-carrier as guard band, the aforementioned problem is solved, and the transmissions of the two users are well separated. The corresponding results shown in Fig. 2 comply with this argument.

We now continue to examine an unsynchronized scenario as described in Section II-A where the symbol timing offset with respect to each user is assumed to be in the range of $(T/8, T/4)$. The other parameters and settings are the same as introduced in previous text. Fig. 3 shows the BER performances of CP-OFDM and FBMC/OQAM in the presence of symbol timing offsets. The impacts of different sizes of the guard band on CP-OFDM and FBMC/OQAM are illustrated, respectively. It can be seen that when there is no guard

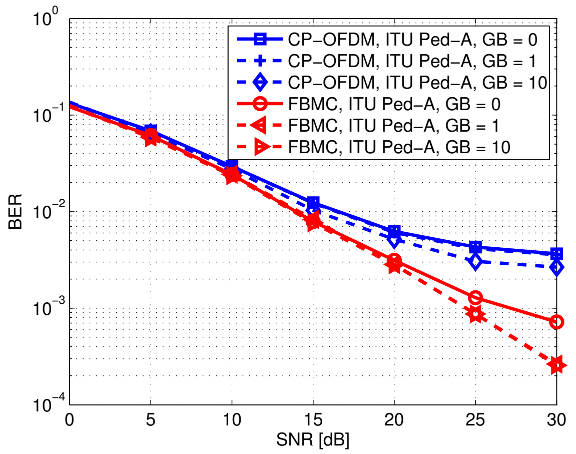

Fig. 3. Comparison between FBMC/OQAM and CP-OFDM for a 2-user uplink scenario in the presence of symbol timing offsets in the range of $(T/8, T/4)$ (GB - guard band in the number of sub-carriers)

band, FBMC/OQAM significantly outperforms CP-OFDM. With a single sub-carrier as the guard band, a performance improvement is observed in case of FBMC/OQAM, while for CP-OFDM the gain compared to the zero-guard-band case is negligible. As the size of the guard band is increased to 10 sub-carriers, we can only see a very slight improvement for CP-OFDM, and it still suffers from an error floor. On the other hand, it can be observed that for FBMC/OQAM when one sub-carrier is used as the guard band, the performance is as good as that in the case of 10 sub-carriers. These results corroborate the theory that as FBMC/OQAM systems are endowed with an agile spectrum, guard bands with very small sizes suffice to isolate groups of sub-carriers for different users or services. In addition, by comparing the results in Fig. 3 to those in Fig. 2, it can be noticed that for the case of FBMC/OQAM the performance degradation compared to the perfect synchronization scenario is quite small. By contrast, such a performance gap for the CP-OFDM-based system is much more significant.

We further show results for a 4-user scenario in Fig. 4. The other simulation parameters are same as described in

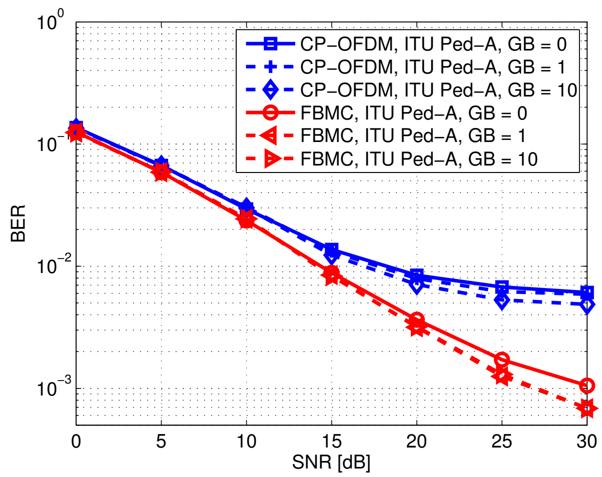

Fig. 4. Comparison between FBMC/OQAM and CP-OFDM for a 4-user uplink scenario in the presence of symbol timing offsets in the range of $(T/8, T/4)$ (GB - guard band in the number of sub-carriers)

the first experiment. Similar observations can be made that FBMC/OQAM is more robust against symbol timing offsets compared to CP-OFDM. Moreover, the size of the guard band required to separated different groups of sub-carriers is substantially smaller than that for CP-OFDM.

B. *Uplink transmissions with residual carrier frequency offsets*

Next we compare CP-OFDM with FBMC/OQAM in an uplink scenario where the residual carrier frequency offset is present by means of numerical simulations. In the first example, a 2-user scenario is considered. The two users and the base station are each equipped with two antennas, and the block-wise sub-carrier allocation scheme is adopted. The ITU Vehicular-A channel model [12] is used in the simulations. Moreover, the users are assumed to be perfectly synchronized in the time domain. Fig. 5 shows the BER performances of CP-OFDM and FBMC/OQAM in the presence of the residual carrier frequency offset. As the maximum possible value of the

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residual carrier frequency offset is increased to 0.15, we observe a significant performance degradation for CP-OFDM due to inter-carrier interference. By comparison, FBMC/OQAM shows a greater robustness against frequency misalignments, as the performance loss is much smaller compared to that of CP-OFDM when the residual carrier frequency offset increases. Meanwhile, FBMC/OQAM outperforms CP-OFDM in both cases.

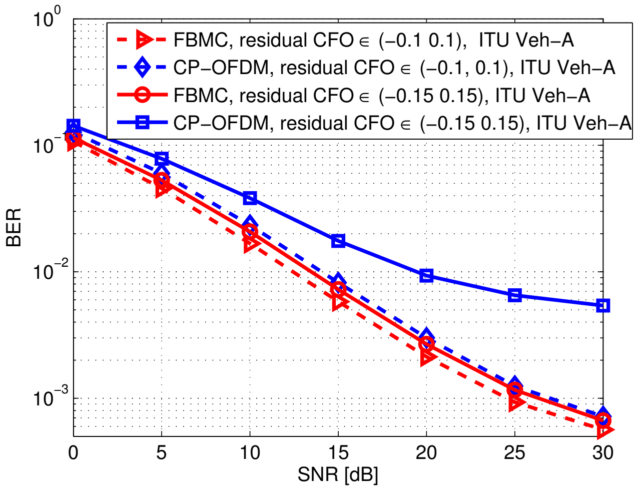

Fig. 5. Comparison between FBMC/OQAM and CP-OFDM for a 2-user uplink scenario in the presence of residual carrier frequency offsets

Second, a 4-user scenario is investigated. The other simulation parameters are the same as in the first example. The corresponding results are illustrated in Fig. 6. Similarly, it can be seen that CP-OFDM is more sensitive to the residual carrier frequency offset compared to FBMC/OQAM. When the residual carrier frequency offset is increased, the gap of performances between FBMC/OQAM and CP-OFDM is larger. It should be noted that in addition to the frequency misalignment, another factor that affects the performance of FBMC/OQAM is the multi-path channel considered in this example. If the channel delay spread is greater than the multi-carrier symbol period, the transmission suffers from inter symbol interference. Nevertheless, the receive processing technique employed in this work as described in Section III (actually a one-tap equalizer) is a straightforward extension of the linear MMSE receiver in CP-OFDM systems. It does not suffice to provide a satisfactory performance. When a multi-tap equalizer [13] is used for FBMC/OQAM, a performance improvement can be expected.

V. Conclusion

Our focus in this contribution is on the performance evaluation of FBMC/OQAM in multi-user MIMO uplink scenarios suffering from a lack of perfect synchronization in the time domain and the frequency domain. Without limiting our investigations to the case of single-antenna nodes or the AWGN channel as in [4] , we present a thorough overview of multi-carrier multi-user MIMO uplink transmissions taking into consideration the effects of timing and frequency misalignments. Through extensive simulation results, it is shown

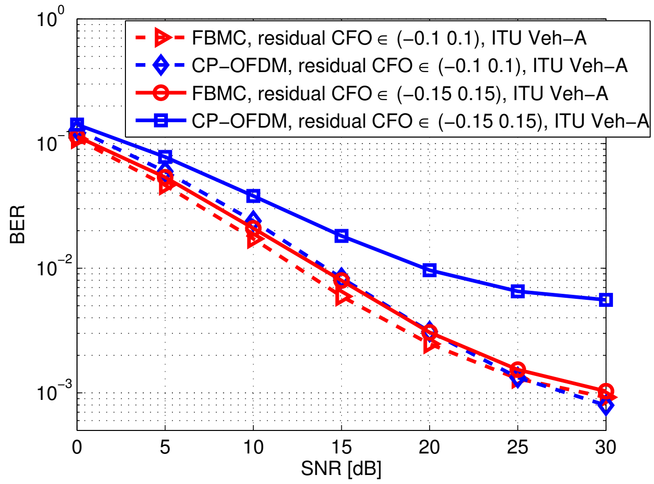

Fig. 6. Comparison between FBMC/OQAM and CP-OFDM for a 4-user uplink scenario in the presence of residual carrier frequency offsets

that FBMC/OQAM systems are more robust against symbol timing offsets compared to CP-OFDM. For FBMC/OQAM, one-sub-carrier guard bands are sufficient to achieve a good isolation of sub-carrier groups belonging to different users, which corroborates the theoretical analysis. On the other hand, CP-OFDM-based systems still suffer from performance degradation, though substantially larger guard bands are employed. In addition, it is also demonstrated that FBMC/OQAM is more immune to residual carrier frequency offsets than CP-OFDM that may require additional efforts in combating the multiple access interference due to frequency misalignments. For the purpose of comparison, CP-OFDM is also discussed and considered in the numerical experiments.

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