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A Precoded Multiuser OFDM (PMU-OFDM) Transceiver for Time Asynchronous Systems

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Abstract— **The performance of a multiuser OFDM transceiver, proposed by authors in [10] and called the precoded multiuser OFDM (PMU-OFDM) in this work, with time asynchronous access is investigated. We show that the multiaccess interference (MAI) due to time asynchronous access can be reduced to a negligible amount by adopting a proper precoder that uses $M/2$ symmetric or $M/2$ anti-symmetric codewords of the M Hadamard-Walsh codes for the precoding task. The PMU-OFDM transceiver with the same precoder was shown to have approximately MAI-free property in a frequency asynchronous environment [11]. Here, we analyze the the approximately MAI-free property of the PMU-OFDM system with respect to time asynchronism. Finally, computer simulation is performed to confirm the derived property.**

Index Terms—multiuser OFDM, PMU-OFDM, MAI-free, time offset, multiuser detection (MUD), OFDMA, code selection.

I. Introduction

Multiuser OFDM systems have received a lot of attention recently [4], [5], since they inherit the advantage of single user OFDM systems [1], [2] in combating the inter-symbol-interference (ISI) and enable high speed data rate transmission. In multiuser OFDM systems such as multicarrier (MC-) CDMA [4] and orthogonal frequency division multiple access (OFDMA) systems [5], users transmit their signals simultaneously so that multiaccess interference (MAI) due to several sources will occur.

Under a single user environment, MC-CDMA systems can provide a full frequency diversity gain if the maximum ratio combing (MRC) technique [4] is used at the receiver. Under a frequency-selective fading environment, the orthogonal code will lose its orthogonality in MC-CDMA systems. If the system has more than one user, the loss of orthogonality will lead to MAI. To suppress MAI, sophisticated multiuser detection or signal processing methods are needed [4]. Under this situation, the full diversity gain offered by the MRC technique can be lost. Moreover, the time and frequency offsets will also cause MAI, which makes the estimation and compensation for time and frequency offsets in MC-CDMA systems much more complicated. Similarly, OFDMA systems are MAI-free when time and frequency are well synchronized, and the technique has been recently adopted for broadband wireless access in the IEEE 802.16 standard [5]. However, OFDMA systems are sensitive to frequency asynchronism, *i.e.* carrier frequency offset (CFO). The CFO effect will lead to significant MAI in OFDMA systems. Furthermore, in uplink transmission, it is difficult to guarantee that signals from all users are well aligned at the receiver end. Thus, time asynchronism may occur among users, which leads to MAI effect as well [7].

Although time asynchronism can be handled using a sufficiently long cyclic prefix to compensate time offsets, this solution increases redundancy and decreases the actual data rate. Another way to address the time offset is to use the Global Positioning System (GPS). However, GPS demands a higher implementational cost. Some research has been conducted using sophisticated signal processing to estimate time and frequency offsets, *e.g.* [6]. Due to MAI, time and frequency offsets cannot be well compensated in the receiver [6]. Offsets have to be estimated by the receiver and sent back to every user via feedback so that each user can compensate the offsets at the transmitter. In the IEEE 802.16 standard, this is done using a feedback mechanism called ranging [5]. Although the time offset problem can be solved using GPS or feedback, either solution imposes a higher computational load on the system. Moreover, it may not guarantee that all users are perfectly synchronized. If some users fail to synchronize with the base station, MAI will occur and the system performance will degrade.

Based on the above discussion, a technique that is robust to both time and frequency offsets is desirable. However, little research has been done in the design of a multiuser OFDM system that is inherently robust to time and frequency offsets. An approximately MAI-free multiaccess OFDM transceiver was proposed in [10] in the presence of CFO. When the number of subchannels is sufficiently large, the proposed system is inherently MAI-free so that there is no need to suppress MAI in the receiver. The CFO effect is effectively mitigated via proper code design in this system [11]. Since the proposed scheme precodes every user with a Hadamard-Walsh code to achieve a multiuser system, it is called the precoded multiuser OFDM (PMU-OFDM) system in this work. The robustness of PMU-OFDM with respect to frequency asynchronism (*i.e.* CFO) was proved analytically and demonstrated numerically. In this work, we extend the result in [11] and show that the PMU-OFDM system is also robust to the time offset by choosing the $M/2$ symmetric or anti-symmetric codewords of the M Hadamard-Walsh codes to precode every user in the system. Then, the MAI caused by the time offset can be reduced to a negligible amount so that the multiuser system behaves like a "single-user" system.

It was shown in [11] that the use of symmetric or anti-

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symmetric Hadamard-Walsh codes can effectively mitigate the frequency offset effect. Combined with the result in this work, we conclude that the system is robust to both time and frequency asynchronism. The new results in this work enables the PMU-OFDM system to have several important advantages. First, algorithms developed for single-user OFDM systems can be used to estimate time offsets, *e.g.* [9]. Second, time offsets for all users can be compensated at the receiver since time misalignment among users only cause negligible MAI and there is no need to use the feedback mechanism as that in OFDMA systems. Third, since PMU-OFDM tolerates larger time offsets, a simple synchronization mechanism can be used in the transceiver design. Finally, even if some users fail to get synchronized with the base station, they will not cause significant performance degradation. Our simulation results corroborate the derived theoretical results.

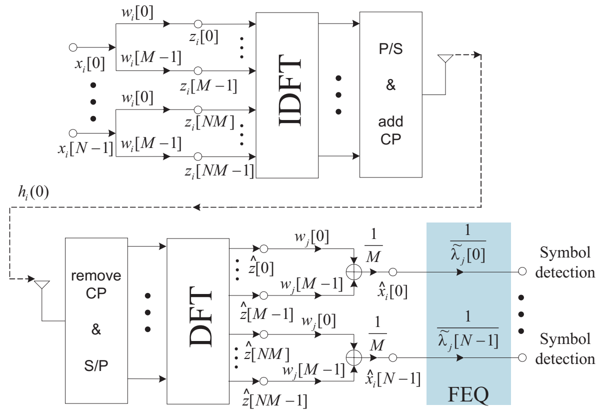

Fig. 1. The block diagram of a PMU-OFDM system.

II. System Model and Its Properties

A brief review of the PMU-OFDM system [10], [11] is given in this section. The block-diagram of the PMU-OFDM system in the uplink direction is shown in Fig. 1, where the signal path demonstrates that the signal transmitted by user i and detected by user j. The input of user i is an $N \times 1$ vector $\mathbf{x}_i$, which contains N modulation symbols such as PSK or QAM. Each symbol in vector $\mathbf{x}_i$ is spread by M in the frequency domain. We consider an orthogonal code of length M and the N symbols of a user will be multiplied by the same code, *i.e.* the short code scenario. The code $w_i[m]$, $0 \le m \le M-1$, for user i satisfies

$$\sum_{m=0}^{M-1} w_i[m]w_j^*[m] = \begin{cases} M, & i = j \\ 0, & i \neq j \end{cases}. \quad (1)$$

Hence, after spreading, the $(m+kM)$th element of the $NM \times 1$ vector $\mathbf{z}_i$ is given by

$$z_i[m+kM] = w_i[m]x_i[k], \quad 0 \le m \le M-1,\ 0 \le k \le N-1. \quad (2)$$

Then, $\mathbf{z}_i$ is passed through the NM-point unitary inverse discrete Fourier transform (IDFT) matrix. Finally, symbols at the IDFT output are converted from the parallel to the serial representation and the cyclic prefix (CP) of length $L-1$ is added, where L is the maximum multipath length.

At the receiver end, the receiver removes the CP and passes each block of size NM through the unitary discrete Fourier transform (DFT) matrix. To detect symbols transmitted by the jth user, the DFT output vector is multiplied by $\mathbf{W}_j^*$ and then averaged. Let $\hat{\mathbf{z}}$ be the DFT output and $\hat{\mathbf{x}}_j$ be the averaging output. The kth element of $\hat{\mathbf{x}}_j$ is given by

$$\hat{x}_j[k] = \frac{1}{M}\sum_{m=0}^{M-1} \hat{z}[m+kM]w_j^*[m], \quad 0 \le k \le N-1. \quad (3)$$

Finally, $\hat{\mathbf{x}}_j$ is passed through frequency equalization (FEQ) [1] and ready for detection. Note that the gain multiplication of PMU-OFDM is after summation, which stands in contrast to MC-CDMA systems [4], where the gain multiplication is before summation.

The PMU-OFDM has an important property, namely, it is approximately MAI-free, described as follows [10], [11]: Let $\lambda_i[l]$ be the lth element of the NM-point DFT of the ith channel path. The lth element of $\hat{\mathbf{z}}$ is given by [1]

$$\hat{z}[l] = \sum_{i=1}^{T} r_i[l] + e[l], \quad 0 \le l \le NM-1, \quad (4)$$

where $r_i[l] = \lambda_i[l]z_i[l]$ and $e[l]$ is the noise after DFT. Let $l = m + kM$. From (2), (3) and (4), the kth element of $\hat{\mathbf{x}}_j$ is given by

$$\hat{x}_j[k] = s_j[k] + \sum_{i=1, i\neq j}^{T} MAI_{j\leftarrow i}[k] + \widetilde{e}_j[k], \quad (5)$$

where $s_j[k] = \frac{1}{M}\sum_{m=0}^{M-1} r_j[m+kM]w_j^*[m]$ is the desired signal of user j, $MAI_{j\leftarrow i}[k] = \frac{1}{M}\sum_{m=0}^{M-1} r_i[m+kM]w_j^*[m]$ is the MAI of user j due to user i, and $\widetilde{e}_j[k] = \frac{1}{M}\sum_{m=0}^{M-1} e[m+kM]w_j^*[m]$. When N is sufficiently larger than the multipath length L, the coherent bandwidth is large. In this case, the frequency response for adjacent subchannels only varies a little. Therefore, we have the approximation

$$\lambda_i[m+kM] \approx \widetilde{\lambda}_i[k], \quad 0 \le m \le M-1,\ 0 \le k \le N-1, \quad (6)$$

where $\widetilde{\lambda}_i[k]$ is the kth component of the averaged frequency gain, $\frac{1}{M}\sum_{m=0}^{M-1} \lambda_i[m+kM]$. Using this approximation and (1), it can be easily shown that $MAI_{j\leftarrow i}[k]$ is zero approximately [10], [11]. Hence, when N is sufficiently large, the PMU-OFDM has approximately MAI-free property. In this situation, we can approximately reconstruct $x_i[k]$ by multiplying $\hat{x}_i[k]$ by $\left(\widetilde{\lambda}_i[k]\right)^{-1}$. The one-tap gain multiplication is what usually called frequency equalization (FEQ) [1].

Although PMU-OFDM uses orthogonal codes to distinguish different users, the approximate zero MAI property makes it significantly different from conventional MC-CDMA systems in many aspects. Instead, it has more similarities to OFDMA as explained below.

(1) Detection: Due to MAI, sophisticated multiuser detection (MUD) may be involved in MC-CDMA system so that detection of individual symbols is dependent [4]. In the

PMU-OFDM and OFDMA system, there is no need of using MUD, and detection of individual symbols is independent. (2) Loading: PMU-OFDM can achieve approximately MAI-free when N is sufficiently large. Hence, by increasing N, the system can be fully loaded with negligible MAI. Also the OFDMA system can be fully loaded with no MAI. In contrast, the number of supportable users in MC-CDMA systems is much less than the spreading factor M due to MAI [4]. (3) Frequency diversity: Although PMU-OFDM may lose the frequency diversity when compared with MC-CDMA, it can achieve the full loading capacity while maintaining the MAI-free property. The diversity gain of PMU-OFDM is close to that of OFDMA.

III. Time Asynchronism Analysis

Time mismatch among users leads to two impairments in the PMU-OFDM system: MAI caused by timing asynchronism of other users and the interference caused by this user's own asynchronism. Once MAI becomes negligible, the timing of an individual user can be more easily estimated and then compensated at the receiver. In this section, we analyze the MAI effect caused by the time offset in PMU-OFDM. Moreover, we show that the MAI due to time asynchronism can be greatly mitigated by proper code design.

Assume the OFDM-block extracting time is at index 0. Let τ_i be the time offset of user i. At the output of DFT, the lth component of $\hat{z}[l]$ due to time asynchronism can still be represented by (4). However, now $r_i[l]$ is the distorted symbol of $z_i[l]$. The distortion is caused by the fading channel and the phase rotation that is due to time delay. When $NM >> |\tau_i|$, the inter-block-interference (IBI) due to time asynchronism is much smaller than the desired signal. Under this situation, we can ignore IBI and have the following approximation [8]

$$r_i[l] \approx \lambda_i[l] z_i[l] e^{j\frac{2\pi}{NM}l\tau_i}. \tag{7}$$

Under time asynchronism, $\hat{x}_j[k]$ can also be represented by (5). For convenience, we define $\phi_{i,j}[m]$ as

$$\phi_{i,j}[m] = w_i[m]w_j^*[m]. \tag{8}$$

Using (2) and (7), $s_j[k]$ in (5) can be rewritten as

$$s_j[k] \approx \frac{1}{M} x_j[k] e^{j\frac{2\pi}{N}k\tau_j} \sum_{m=0}^{M-1} \lambda_j[m+kM]\phi_{i,j}[m] e^{j\frac{2\pi}{NM}m\tau_j}. \tag{9}$$

When $N >> |\tau_j|$, $e^{j\frac{2\pi}{NM}m\tau_j} \approx 1$. Using (1) and the approximation in (6), we can approximated $s_j[k]$ by

$$s_j[k] \approx \widetilde{\lambda}_j[k] x_j[k] e^{-j\frac{2\pi}{N}k\tau_j}. \tag{10}$$

As shown in (10), we see that there is a phase rotation term due to time asynchronism. Now, let us examine the MAI term in (5) under time asynchronism. From (2) and (7), we have

$$MAI_{j\leftarrow i}[k] = \frac{1}{M} x_i[k] e^{j2\pi\frac{k\tau_i}{N}} \sum_{m=0}^{M-1} \lambda_i[m+kM]\phi_{i,j}[m] e^{j2\pi\frac{m\tau_i}{NM}}. \tag{11}$$

Using the same argument from (9) to (10), we have

$$MAI_{j\leftarrow i}[k] \approx \frac{1}{M}\widetilde{\lambda}_i[k] x_i[k] e^{j2\pi\frac{k\tau_i}{N}} \mathcal{O}, \tag{12}$$

where $\mathcal{O} = \sum_{m=0}^{M-1}\phi_{i,j}[m]e^{j2\pi\frac{m\tau_i}{NM}}$. Since $e^{-jx} = \cos x - j\sin x$, we can manipulate $\mathcal{O}$ in (12) as

$$\mathcal{O} = \sum_{m=0}^{M-1}\phi_{i,j}[m]\left[\cos\left(\frac{2\pi}{NM}m\tau_i\right) - j\sin\left(\frac{2\pi}{NM}m\tau_i\right)\right]. \tag{13}$$

When $N >> |\tau_i|$, the maximum value of $\frac{2\pi}{NM}m|\tau_i|$ is less than $\pi/2$. Under this situation, the function $f_1(m) = \cos\left(\frac{2\pi}{NM}m\tau_i\right)$ can be approximated by a linear function passing through $f_1(0)$ and $f_1(M)$ given by

$$\cos\left(2\pi\frac{m\tau_i}{NM}\right) \approx \frac{f_1(M)-1}{M}m+1, \quad 0 \le m \le M-1. \tag{14}$$

Similarly, the function $f_2(m) = \sin\left(2\pi\frac{m\tau_i}{NM}\right)$ can be approximated by a linear function passing through $f_2(0)$ and $f_2(M)$ given by

$$\sin\left(2\pi\frac{m\tau_i}{NM}\right) \approx \frac{f_2(M)}{M}m, \quad 0 \le m \le M-1. \tag{15}$$

The approximations in (14) and (15) become more accurate as N increases. Using (14) and (15), we can rewrite (13) as

$$\begin{aligned}\mathcal{O} &\approx \sum_{m=0}^{M-1}\phi_{i,j}[m]\left[\left(\frac{f_1(M)-1}{M}m+1\right) - j\left(\frac{f_2(M)}{M}m\right)\right] \\ &= \left(\frac{f_1(M)-1}{M} - j\frac{f_2(M)}{M}\right)\sum_{m=0}^{M-1}\phi_{i,j}[m]m. \end{aligned} \tag{16}$$

With (16), we can rewrite (12) as

$$MAI_{j\leftarrow i}[k] \approx \frac{1}{M}\widetilde{\lambda}_i[k] x_i[k] e^{j2\pi\frac{k\tau_i}{N}} \left(\frac{f_1(M)-1}{M} - j\frac{f_2(M)}{M}\right)\mathcal{O}', \tag{17}$$

where $\mathcal{O}' = \sum_{m=0}^{M-1}\phi_{i,j}[m]m$. As shown in (17), when N is sufficiently large, we have $f_1(M) \approx 1$ and $f_2(M) \approx 0$. Hence $MAI_{j\leftarrow i}[k] \approx 0$. Furthermore, if $\mathcal{O}' = 0$, the MAI effect can be further reduced, thus making the system more robust to time asynchronism. It turns out that certain subsets of Hadamard-Walsh codes satisfy this property. From [3], the M Hadamard-Walsh code can be divided into two groups of $M/2$ codewords: the set of symmetric (even) codes satisfying

$$w_i[m] = w_i[M-1-m], \quad 0 \le m \le M/2-1, \tag{18}$$

and the set of anti-symmetric (odd) codes satisfying

$$w_i[m] = -w_i[M-1-m], \quad 0 \le m \le M/2-1. \tag{19}$$

Based on (1), (18) and (19), we have the following lemma.

Lemma. Suppose that only $M/2$ symmetric or anti-symmetric codewords of the M Hadamard-Walsh codes are used. The product of any two codewords within the $M/2$ selected codewords, $w_i[m]w_j^*[m]$, satisfies the following property

$$\sum_{m=0}^{M/2-1} w_i[m]w_j^*[m] = \begin{cases} M/2, & i=j \\ 0, & i \ne j \end{cases}. \tag{20}$$

This leads to the following main proposition of this work.

Proposition. Suppose that only $M/2$ symmetric or anti-symmetric codewords of the M Hadamard-Walsh codes are used, $\mathcal{O}'$ defined in (17) equals zero, *i.e.*

$$\mathcal{O}' = \sum_{m=0}^{M-1} w_i[m]w_j^*[m]m = 0. \tag{21}$$

Hence, the MAI effect due to time offset can be greatly reduced.

Proof. Using (8), divide $\sum_{m=0}^{M-1} \phi_{i,j}[m]m$ into two terms via

$$\sum_{m=0}^{M-1} \phi_{i,j}[m]m = \sum_{u=0}^{M/2-1} \phi_{i,j}[u]u + \sum_{v=M/2}^{M-1} \phi_{i,j}[v]v \qquad (22)$$

Let $v = M-1-u$. Using either (18) or (19), the second term of (22) can be manipulated as

$$\sum_{v=M/2}^{M-1} \phi_{i,j}[v]v = (M-1) \sum_{u=0}^{M/2-1} \phi_{i,j}[u] - \sum_{u=0}^{M/2-1} \phi_{i,j}[u]u. \qquad (23)$$

Using (20), (22) and (23), we are led to (21). ■

Although the number of users is decreased by one half using symmetric or anti-symmetric Hadamard-Walsh codewords, the resulting system is approximately MAI-free in the presence of time offset. It has been shown that the same code design can mitigate the MAI effect caused by frequency offset [11], which is a serious impairment that limits the mobility of OFDMA systems. Therefore, the use of symmetric or anti-symmetric Hadamard-Walsh codewords makes PMU-OFDM inherently MAI free in a time- and frequency-asynchronous environment.

When the MAI effect due to time asynchronism is negligible, the timing estimation for each individual user becomes easier, *i.e.* estimation algorithm used in single user environment may be applied here without worrying about MAI. Moreover, timing misalignment among users can be compensated in the receiver end. For instance, the receiver can extract individual users' OFDM block at the corresponding correct timing for detection. Even when the timing misalignment of other users exists, it will only cause negligible MAI and will not degrade the system BER performance much. Examples 1-2 in Sec. IV will confirm this point. These results stand in contrast to those of the OFDMA system, where minor timing mismatch will cause significant MAI [7]. As mentioned in [6], the timing asynchronism of OFDMA cannot be solved in the receiver alone and a feedback mechanism is demanded. If some users fail to be synchronized, some sophisticated multiuser estimation algorithm [6] is demanded to acquire the time offset information of users.

IV. Simulation Results

In this section, computer simulation is conducted to corroborate the theoretical results derived in previous sections. We consider the performance in the uplink direction so that every user has a different time offset and channel fading. The channel and the time offset are assumed to be quasi-invariant in the sense that they remain unchanged within one OFDM-block duration. Simulations are conducted with the following parameter setting throughout this section: $N = 128$, $M = 16$ and the BPSK modulation. For every user, the Monte Carlo method is used to run more than 500,000 symbols. We consider the worst time offset case where, except for the target user who is assumed to have the correct timing, *i.e.* zero time offset, the time offsets of all other users are randomly assigned to be either $+\tau$ or $-\tau$. All T users are chosen to be the target user in turn. Moreover, the CP length $\nu = L-1$ is added. In this situation, any non-zero time offset will lead to MAI.

We compare the performance of PMU-OFDM and OFDMA systems. Every user in these two systems transmits N symbols while the DFT/IDFT size is the same, *i.e.* NM. Since the two systems transmit N symbols per block and add the CP of the same length ν, their actual data rates are the same. We consider both fully-loaded and half-loaded situations. For a fully-loaded OFDMA system, each user occupies N subchannels which are maximally separated, *i.e.* user u is assigned subchannels indexed by $(u-1)+kM$, $1 \le u \le M$ and $0 \le k \le N-1$. For a half-loaded OFDMA system, user u is assigned subchannels indexed by $2(u-1)+kM$, $1 \le u \le M/2$ and $0 \le k \le N-1$. The remaining $NM/2$ subchannels are used as guard bands.

Example 1. The flat fading channel case

We first evaluate the MAI effect after FEQ $MAI'_{j\leftarrow i}[k]$, *i.e.* $MAI'_{j\leftarrow i}[k] = MAI_{j\leftarrow i}[k]/\widetilde{\lambda}_i[k]$. The averaged total MAI after FEQ is obtained by averaging the value, $\frac{1}{T}\sum_{j=1}^{T} \frac{1}{N}\sum_{k=0}^{N-1} \left|\sum_{i=1,i\ne j}^{T} MAI'_{j\leftarrow i}[k]\right|^2$, for more than 500,000$T$ symbols. The averaged total MAI after FEQ for PMU-OFDM and OFDMA under the fully- and the half-loaded situations with respect to a flat fading channel are shown in Fig. 2. For the fully-loaded situation, PMU-OFDM outperforms OFDMA when the time offset $\tau \le 5$. However, its performance is worse than OFDMA as $\tau > 5$. For the half-loaded case, we see that the use of the symmetric codewords can greatly reduce MAI by around 20-43 dB when compared to the fully-loaded case. On the other hand, the performance of OFDMA is only slightly improved from the full load to the half load. We see that PMU-OFDM outperforms OFDMA by around 14-48 dB in the half-loaded situation.

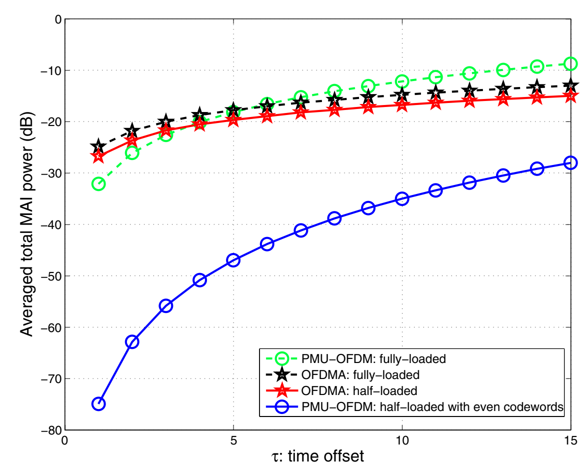

Fig. 2. The MAI comparison between PMU-OFDM and OFDMA with a flat fading channel.

Now, let us assume that every user, except for the target user, has a time offset of $|\tau_i| = 13$ in the two systems. All the T users will be the target user in turn. We would like to evaluate the bit error rate (BER) when there is no feedback. The BERs for the two systems are shown in Fig. 3. For the benchmarking purpose, we also show the curve for OFDMA without time offset. We see from this figure that, even in a serious timing mismatch environment, PMU-OFDM with the proposed code scheme can achieve performance comparable to OFDMA without time offset.

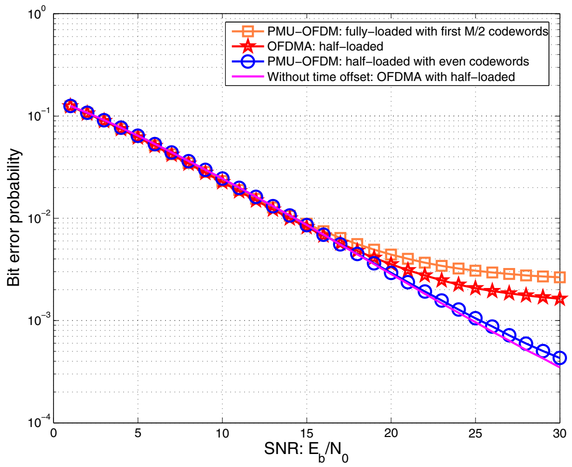

Fig. 3. The BER comparison between PMU-OFDM and OFDMA in a flat channel with time offset $|\tau_j| = 13$.

Example 2. The multipath channel case

In this example, we examine the time asynchronous effect in a multipath channel. The number of multipath is assumed to be $L = 4$ while the other parameters remain the same as given in Example 1. The channel coefficients are i.i.d. complex Gaussian random variables with an unit variance. The MAI performance of PMU-OFDM and OFDMA is compared in Fig. 4. In a fully-loaded situation, OFDMA has less MAI than PMU-OFDM. However, in a half-loaded situation, PMU-OFDM outperforms OFDMA by around 13-25 dB with the proposed code scheme.

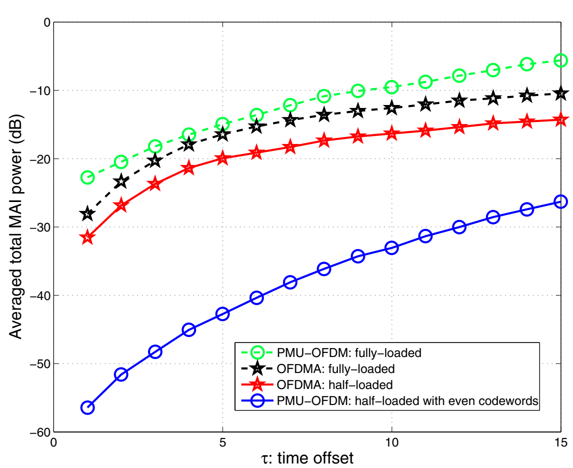

Fig. 4. The MAI comparison between PMU-OFDM and OFDMA in a frequency-selective channel.

Fig. 5 shows the BER comparison among the two systems with $|\tau_i| = 13$ in a half-loaded situation. We see that PMU-OFDM with the proposed code does not have a significant performance floor in such a serious time asynchronous and frequency-selective channel. For comparison, we plot the BER performance of PMU-OFDM with the first $M/2$ Hadamard-Walsh codes as precoding codes. Its performance is close to that of a half-loaded OFDMA system, but far worse than the proposed code scheme. This shows the importance of a proper code design in a time asynchronous case for PMU-OFDM.

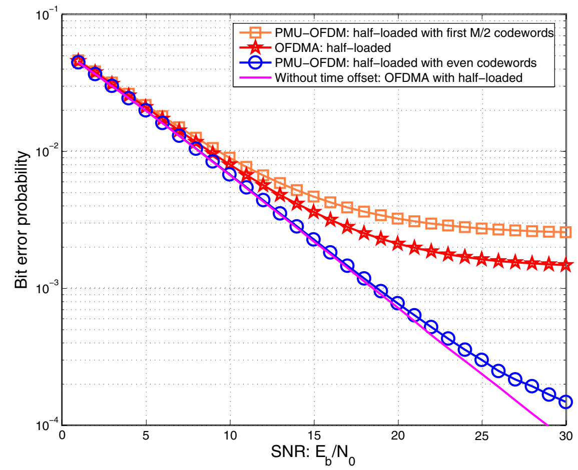

Fig. 5. The BER comparison between PMU-OFDM and OFDMA in a frequency-selective channel with $L = 4$ and time offset $|\tau_j| = 13$.

V. Conclusion

The time asynchronism effect in the PMU-OFDM system was studied. It was shown analytically and by computer simulation that the MAI effect due to time offset effect can be reduced using either the $M/2$ symmetric or anti-symmetric codewords of the M Hadamard-Walsh codes. As a result, a simpler time asynchronization mechanism can be adopted in the transceiver design.

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