Block-Iterative Frequency-Domain Equalizations for SC-IDMA Systems

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ABSTRACT

In wireless broadband communications using single-carrier interleave division multiple access (SC-IDMA) systems, efficient multiuser detection (MUD) classes that make use of joint hybrid decision feedback equalization (HDFE)/ frequency decision-feedback equalization (FDFE) and interference cancellation (IC) techniques, are proposed in conjunction with channel coding to deal with several users accessing the multipath fading channels. In FDFE-IDMA, the feedforward (FF) and feedback (FB) filtering operations of FDFE, which use to remove intersymbol interference (ISI), are implemented by Fast Fourier Transforms (FFTs), while in HDFE-IDMA the only FF filter is implemented by FFTs. Further, the parameters involved in the FDFE/HDFE filtering are derived according to the minimum mean square error (MMSE) criteria, and the feedback symbol decisions are directly designed from soft detection of the decoded signals at the previous iteration. The simulation results including comparisons with those of frequency domain equalization (FDE), SC-FDE-IDMA and multi-carrier OFDM-IDMA schemes, with cyclic prefixing (CP) and zero padding (ZP) techniques, show that the combination of FDFE-IC/HDFE-IC provides an efficient solution with good performance for IDMA systems in ISI channels. Moreover, these iterative structures with block equalization yield a much lower complexity than equivalent existing structures, making them attractive for a wealth of applications.

Key words: frequency-domain equalization, interference cancellation.

التعادلات الكتلية- المتكررة وبمجال ترددي لأنظمة (SC-IDMA)

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الخلاصة

في الأتصالات المذاعة اللاسلكية بأستخدام حاملة منفردة لأنظمة (IDMA) , أصناف اكتشاف المستخدم الكفوء التي تستخدم تقنيات ازالة التشويش مع (HDFE) او (FDFE) اقترحت بالترابط مع تشفير القناة للتعامل مع عدة مستخدمين عبر قنوات المسارات المتعددة. في (FDFE-IDMA) ,عمليات الفلترة الأمامية والخلفية في (FDFE) والتي تستخدم لأزالة التشويش البيني (ISI) قد تم انجازها بأستخدام (FFTs), بينما في (HDFE-IDMA) فقط الفلتر الأمامي تم أنجازه باستخدام (FFTs) . وكذلك المتغيرات الموجودة في فلترة (FDFE/HDFE) قد تم اشتقاقها نسبة الى قاعدة (MMSE), وقرارت القيم المعادة قد تم تصميمها من الأكتشاف المرن للأشارات المشفرة بالتكرار السابق. نتائج المحاكاة المتضمنة مقارنات مع تلك التي تتضمن المعادلة بمجال التردد (FDFE), أنظمة (FDE-IDMA) و (OFDM-IDMA) مع تقنيات (CP) و(ZP), أظهرت بأن تركيبات (FDFE-IC/HDFE-IC) توفر حل كفوء مع أداء جيد لأنظمة (IDMA) في قنوات (ISI) . وكذلك فان هذه التراكيب المتكررة مع التعادل الكتلي تنتج تخفيض كبير للتعقيدات الرياضية من تلك التراكيب الموجودة وبذلك تجعلها جذابه للعديد من التطبيقات.

الكلمات الرئيسية: تعادل المجال الترددي، الغاء التشويش.

1. INTRODUCTION

In recent years, wireless communication systems have been widely used to offer a broadband access on a common channel and deliver high-data-rate in numerous applications, which range from wireless LANs, to digital audio and video broadcasting. Further, the latest wireless systems require low power consumption and low complexity to support various applications on multiple access channels. Therefore, multiple access schemes are needed to share and allocate the channel resources to multiple users, causing multiple access interference (MAI) and significant multipath channel distortion. To compensate for such distortion, various architectures based on IDMA systems, **,Weitkemper, et al., 2008 ,Ping, et al., Oct. 2007 ,Guo, et al., 2006** and **Guo, et al., 2008** had been proposed in literature.

For moderately dispersive channels, the Rake based IDMA receiver **,Weitkemper, et al., 2008 ,Ping, et al., 2007 ,Guo, et al., 2006** and **Guo, et al., 2008** is the most common solution that provides a good balance between performance and complexity. The multi-user detection (MUD) in Rake-IDMA receiver has a linear complexity and the related detection costs at the chip rate for such receivers become a serious issue in ISI channels. As the channel dispersion increases, the equalization process become increasingly challenging due to the increase in the number of resolvable paths and the performance of Rake receivers degrades significantly. Moreover, the performance of such schemes with traditional IC schemes is also limited by the MAI from other active users. By combining IDMA and orthogonal frequency division multiplexing (OFDM), an efficient multiuser system, OFDM-IDMA **,Ping, et al., 2007** and **Zhang, et al., 2008**, is formed which efficiently combats ISI by the cyclic prefixing (CP) technique in OFDM, and MAI by iterative detection with IDMA **,Weitkemper, et al., 2008.** With regard to non-linear structures, a time domain (TD) DFE comprises a FF filter, operating at the chip rate, and a feedback (FB) filter has been proposed for IDMA systems on dispersive channels **,Aliesawi, et al., 2011.** While it is attractive for its performance, its complexity comparable to linear equalization (LE) and may be significant, especially for very dispersive channels, due to both the signal processing and the design of the FF and FB filters.

For channels with long-delay spread, SC-IDMA approaches with frequency domain equalization (FDE) in **,Lim, et al., 2007** was computationally simpler than corresponding time domain equalization (TDE), and can reduce some of the RF implementation problems **,Lakshmanan, et al., 2009 ,Falconer** and **Ariyavisitakul, 2002** and **Falconer, et al., 2002.** However, SC-FDE systems have similar performance, efficiency and low signal processing complexity advantages as OFDM, and in addition are less sensitive to RF impairments than OFDM that requires predistortion techniques. More recently, an iterative block IBDFE and hybrid time-frequency domain HDFE structures with a considerable reduction of complexity had been proposed **,Benvenuto and Tomasin, 2002 ,Benvenuto and Tomasin, 2005 ,** and **Benvenuto and Tomasin Jun., 2002.** The HDFE structure does not yield a simple solution for the design of the feedforward filter (FF).

Since filtering operations are implemented in FD by FFT, IBDFE yields a significant lower complexity in the filter design and it does not require any matrix inversion as the case in TDDFE. However, such schemes can be used efficiently with IC techniques to remove both multiple access interference (MAI) and ISI using iterative detection techniques. IBDFE approach was also used for CP assisted SC-CDMA systems in **,Benvenuto** and **Tomasin, Sep. 2005.** By performing various FD operations, the performance of such block-based DFEs, can be improved due to the possibility of selecting longer filters. Further, the classical non-iterative TD-DFE and HDFE based multiuser systems suffer from error-propagation phenomena and are not able to cancel the precursors of the ISI.

In this paper, the application of the HDFE and IBDFE/FDFE structures are extended to SC-IDMA systems. The resulting structures are denoted as HDFE-IDMA and FDFE-IDMA, respectively. The proposed structures have the benefits of a TD-DFE in terms of performance with much lower computational complexity, especially when severely time-dispersive channels are considered due to the FFT based frequency-domain implementation. The paper is organized as follow. In Section 2, the system model and the data transmission format that will be used in the SC-IDMA implementation are described. The iterative structures of the HDFE-IDMA and FDFE-IDMA detectors as well as the description of the HDFE-IC, FDFE-IC and the design of filter coefficients are considered in Section 3. The complexity of the proposed schemes is given in Section 4 and is compared with that of the other structures **,Ping, et al., 2007.** The performance is shown in Section 4 with simulations on downlink broadband communication. In Section 5, the conclusions of the proposed schemes are drawn.

2. DATA TRANSMISSION MODEL

For a wideband IDMA transmission in **Fig.1**, the information bits, $d^k(n)$ of user k are first encoded using error correction code and repetition code, $c^k(m), m = 0,1,\dots,N_s - 1$ with spreading factor N_s. The chips are then interleaved by a user-specific interleaver Π_k. FEC and MUX denote forward error correction and multiplexer device, respectively. The MUX allows one or more input signals to be selected or combine into one transmitted signal. The user-specific interleavers are generated randomly and independently. The obtained data sequence with rate, $1/(TN_s)$, can be written after mapping as **,Dinis, et al., 2007.**

$$s^k(m + nN_S) = \Pi^k[c^k(m)d^k(n)], \;\; k = 0,1,\dots,K-1 \tag{1}$$

where K is the number of active users transmitting simultaneously. The transmitted signal $s^k(n)$ is multiplexed with a training sequence $t^k(n)$ with length that is not lower than the channel length, and then modulated with a pulse-shaping filter that exhibits a raised cosine frequency response.

At the base station, the received signal $r(n)$ is filtered by a matched filter and then sampled at the rate $1/(TN_s)$. By denoting, $h_p^k(n)$, with $p = 0,1,\dots,N_p - 1$, the channel fading coefficients for the user k, the baseband received signal $r(n)$ includes the sum of the signals of all users, can be expressed as

$$r(n) = \sum_{k=0}^{K-1} \sum_{P=0}^{N_{p-1}} h_p^k(n) s^k(n-p) + w(n), \tag{2}$$

where $w(n)$, represents the additive noise process with variance, $\sigma^2 = \frac{N_0}{2}$, and zero mean. In uplink transmission, the channel $h_p^k(n)$ for each user k can be modelled as the sum of delayed paths with different phases and attenuations. Analogously, the received signal in the FD, R, can be written as

$$R = [R_1, R_2, \dots, R_N]^T = \sum_{k=1}^{K} H^k S^K + W, \tag{3}$$

where $[.]^T$ denotes the transpose, S^k, W and H^k are the FFTs of s^k, w, and h^k, respectively **,Lakshmanan, et al., 2009** and **Dinis, et al., 2007.**

3. FDE-DFE BASED SC-IDMA RECEIVERS

The proposed structure in **Fig. 2** processes the received data $r(n)$ in an iterative fashion. For better detection, the hybrid time-frequency domain HDFE or frequency domain FDFE is integrated with IC scheme to combat the effects of both intersymbol interference (ISI) and MAI. In fact, the frequency-domain filtering of HDFE must be performed on a per-block basis, while the feedback section must be fed with the previous detected symbols whose decisions are performed in the TD **,Falconer, et al., 2002** and **Benvenuto and Tomasin, 2002.** The HDFE in **Fig. 3** operates on blocks of the $r(n)$, and after a transient due to the first received samples, FFT is applied to successive blocks of received samples. To avoid the delay inherent in the block FFT signal processing, the FF filter part operates in the FD, while the transversal filtering for the FB part operates in the TD.

The FDFE in **Fig. 4** includes the FF filter coefficients in the FD, W_{FF} with $n = 1, \dots N$, which partially mitigates part of the interference; and the FB filter coefficients W_{FB} with length $n = 1, \dots N$, which removes the residual interference generated by both the pre-cursors and post-cursors of the channel impulse response. The detector takes soft information $r(n)$ and delivers after some processing refined log-likelihood ratios (LLRs) $L_m\ [s^k(n)]$, which are based on *a priori* known information $L_d\ [s^k(n)]$ and the information gained by the equalization.

The effectiveness of HDFE/FDFE with IC filter is limited by the reliability of the detected data at the previous iteration. During each iteration, the filter is applied to a received data, and tentative feedback decisions, $\hat{s}^k(n)$, made in the previous iteration are then used to construct and subtract out an estimate of the ISI and MAI. With each iteration, increasingly refined soft decisions, $\tanh(L_d[s^k(n)/2\ )$, are generated using this strategy. However, the cancellation and detection procedures may be iterated a few times in order to increase the reliability of the detected data.

3.1 HDFE Filter Design

In **Fig. 3**, the FFT output coefficients of the HDFE, $(r(n))$, are multiplied by the complex valued FF coefficients, $\boldsymbol{G}_{FF}(n)$. An IFFT is applied to the equalized complex valued samples, $IFFT(FFT(r(n))\boldsymbol{G}_{FF}(n))$. The estimated ISI due to $\hat{s}^k(n)$ is computed using FB feedback taps and subtracted symbol by symbol from the resulting TD sequence of FF filter.

The soft feedback detected data $\hat{z}\ \ (n)$ at the previous iteration is used as input to the FB filter to generate the FB vector. The FF and FB coefficients are designed in order to minimize the sum of the power of the filtered noise and the power of the residual interference as **,Falconer** and **Ariyavisitakul, 2002. ,Falconer, et al., 2002. ,Benvenuto** and **Tomasin, 2005** and **Benvenuto** and **Tomasin, Jun. 2002.**

$$J_{MMSE} = E\{\ |\tilde{z}(n) - \hat{z}(n)\ |^2\ \}$$

$$= \frac{1}{N}\sum_{n=0}^{N-1} \sigma_w^2 \mid \boldsymbol{G}_{FF}(n)|^2 + \sigma_z^2 |1 - (\ \boldsymbol{G}_{FF}(n)H(n) +\ \boldsymbol{G}_{FB}(n)|^2], \tag{4}$$

by assuming the past decisions are correct and in order to compute filters coefficients, the cost function is written as a function of $\boldsymbol{G}_{FB}(n)$

$$\boldsymbol{G}_{FF}(n) = \frac{H^*(n)(1 - \boldsymbol{G}_{FB}(n))}{|H(n)|^2 + \frac{\sigma_w^2}{\sigma_z^2}}, \tag{5}$$

inserting Eq. (5) in Eq. (4) we obtain

$$J_{MMSE} = \frac{\sigma_w^2}{N} \sum_{n=0}^{N-1} \frac{|1 - \boldsymbol{G}_{FB}(n)|^2}{|H(n)|^2 + \frac{\sigma_w^2}{\sigma_z^2}} \tag{6}$$

by applying the gradient method to minimize the cost function J_{MMSE}, we obtain the linear system of L equations with L unknowns $A_{MMSE}\boldsymbol{w}_{FB} = b_{MMSE}$, where $\boldsymbol{w}_{FB} = [w_{FB,1} \ldots w_{FB,L}]^T$.

$$[A_{MMSE}]_{n,l,m} = \sum_{n=0}^{N-1} \frac{e^{-j2\pi(n(l-m))/N)}}{|H(n)|^2 + \frac{\sigma_w^2}{\sigma_z^2}}, 1 \le m, l \le L_s \tag{7}$$

$$[b_{MMSE}]_m = \sum_{n=0}^{N-1} \frac{e^{-j2\pi(nm/N)}}{|H(n)|^2 + \frac{\sigma_w^2}{\sigma_z^2}}, 1 \le m \le L \tag{8}$$

when $\sigma_w^2 \to 0$, the minimum mean square error (MMSE) solution will reduce to the zero forcing (ZF) solution. Hence, the HDFE output can be described as **,Aliesawi, et al., 2011.**

$$\hat{y}(n) = IFFT(FFT\big(r(n)\big)\boldsymbol{G}_{FF} - \sum_{l=1}^{L} w_{FB}(n)\hat{z}(n). \tag{9}$$

Since the feedback part of the HDFE performs only multiplications and symbol by symbol subtraction of feedback symbols, the FB is also simple and it could be made with L taps as required for adequate performance.

3.2 FDFE Filter Design

In **Fig.** 4, the vector, W_{FF}^{it}, at iteration it, is element-wise multiplied with R_n to produce the output vector Y_{FF}^{it} as

$$Y_{FF}^{it} = W_{FF}^{it} R_n , \tag{10}$$

the feedback detected data $\hat{z}^{it}$, is transformed by a FFT to result $\hat{Z}^{it}$, and then multiplied with W_{FB}^{it}, to yield the FB output vector Y_{FB}^{it} as

$$Y_{FB}^{it} = W_{FB}^{it}\, \hat{Z}^{it}, \tag{11}$$

Since Y_{FB}^{it} depends on the feedback detected data $\hat{z}^{it}$, at the previous iteration, when no detected data is available at, $it = 1$, the $\hat{Z}^{it}$ is set as

$$\hat{Z}^{it} = 0, n = 1, \dots, N \quad (12)$$

At the combining point, the vector signal Y^{it} is obtained as

$$Y^{it} = Y_{FF}^{it} + Y_{FB}^{it}, \quad (13)$$

The Y^{it} is transformed by an inverse discrete Fourier transform (IFFT) to result the TD vector signal as an input to the IC scheme

$$z = \frac{1}{N} W^H Y^{it}, \quad (14)$$

where W^H is the N by N FFT matrix. The outputs of IC scheme after deinterleaving Π_k^{-1} and despreading are sent to the kth user decoder. The output of the decoders after spreading and interleaving Π_k is subtracted from $L_m[s^k(n)]$ to form the extrinsic information of the user k. The effectiveness of the FDFE-IC to cancel the channel effects is limited by the reliability of the detected data at the previous iteration. Indeed, the iterative process gradually increases the reliability of the detected data. However, by performing FDFE filtering operations in the FD through the FFT, the complexity of processing can be reduced.

The FF and FB filters are designed to minimize the resulting mean square error (MSE), where the expectations are taken with respect to the transmitted data, the detected data and the noise. By assuming a *priori* statistic of the involved signals, the correlation among the errors on the data is ignored and the correlation coefficients at iteration (it) can be defined as **,Lakshmanan, et al., 2009 ,Benvenuto and Tomasin, 2005** and **Dinis, et al., 2007.**

$$corr_{z,\hat{z}^{(it-1)}} = E[\, z(n)\hat{z}^{(it-1)}(n)\,], \quad (15)$$

The cost function J^{it}, is written as **,Zhang, et al., 2008** and **Falconer** and **Ariyavisitakul, 2002.**

$$J^{it} = \{ \; |\hat{z}^{it}(n) - z(n)|^2 \}. \quad (16)$$

By applying Parseval's theorem and using Eq. (10), the J^{it} can be written as

$$J^{it} = \frac{1}{N^2} \sum_{n=0}^{N-1} E\{ \; |G_{FF}^{it} R_n + W_{FB}^{it}\, \hat{z}^{(it-1)}\;(n) - z(n)|^2 \}. \quad (17)$$

From substituting Eq. (3), and by taking the expectations in Eq. (17) with respect to the data and the noise, the J^{it} is written as

$$J^{it} = \frac{1}{N^2} \sum_{n=1}^{N} |G_{FF}^{it}|^2 M_w + |G_{FF}^{it}\; H - 1|^2 M_{z(n)} + |W_{FB}^{it}|^2 M_{\hat{Z}^{(it-1)}(n)} + 2Real\left\{ W_{FB}^{(it)^*} \left(G_{FF}^{it}\;(n) H - 1 \right) corr_{z,\hat{z}^{(it-1)}} \right\}, \quad (18)$$

where $M_{z(n)} = E[\quad |S|^2]$, and M_w is the average power of the MAI and noise signals in the FD, respectively. To derive the filters that minimize the above equation, the FB filter imposes the constraint that the filter removes both pre-cursors and post-cursors, but doesn't remove the desired components, i.e, it must be

$$\sum_{n=0}^{N-1} W_{FB}^{it} = 0 \tag{19}$$

By taking the gradient method with respect to the FB filter coefficients, under the above constraint, yields the solution

$$W_{FB}^{it} = \frac{corr_{z,\hat{z}(it-1)} |HG_{FF}^{it} - Gamma^{it}|}{M_{\hat{Z}(it-1)}}, \tag{20}$$

$$Gamma_n^{it} = \sum_{n=1}^{N} H\, G_{FF}^{it}, \tag{21}$$

by inserting W_{FB}^{it} in cost function and setting to zero the gradient with respect to the FF coefficients, we obtain

$$G_{FF}^{it} = \frac{H^*}{M_w + M_{z(n)}(1 - \frac{|corr_{z,\hat{z}(it-1)}|^2}{M_{z(n)} M_{\hat{z}(it-1)(n)}})H^2} \tag{22}$$

On the other hand, when perfect knowledge of the transmitted data is available, the correlation coefficients becomes

$$corr_{z,\hat{z}(it-1)} = M_{z(n)} \quad , \tag{23}$$

and $M_{\hat{z}(n)} = M_{z(n)}$. From Eq. (22) and Eq. (20), the FF filter is matched to the channel, i.e,

$$G_{FF}^{it} = \frac{H^*}{M_{z(n)}}, \tag{24}$$

while the FB filter removes all the ISI. A first estimate of the disturbance power is obtained as in **Benvenuto and Tomasin, 2005**

$$\hat{\sigma}_e^{it} = \sqrt{\frac{1}{N} \textstyle\sum_{n=1}^{N}} |\hat{z}(n)^{it} - z(n)|^2 , \tag{25}$$

3.3 Interference Generation and PIC Scheme

The impact of MAI can be removed by applying a parallel (IC) scheme. In PIC, the MAI produced by the other users accessing the same channel, is removed in parallel for all users. As compared with the successive IC scheme, PIC requires a short processing delay to complete the cancellation operation **,Peijun and Rappaport, 1998.** The soft symbols $z(n)$ after equalization are given to the IC and the LLRs for each user are obtained using **,Aliesawi, et al., 2011.**

$$L_m[s^k(n)] = \frac{2\{z(n) - E[z(n)] + \sum_{k=1}^{K} E[s^k(n)]\}}{\sum_{k=1}^{K} var[s^k(n)] + \sigma_w^2 - var[s^k(n)]}, \forall\, k, n \tag{26}$$

The extrinsic information $L_m[s^k(n)]$, is processed by the deinterleavers and the despreaders. The decoders generate the bit-level extrinsic LLRs, which are also processed by the interleavers and the spreaders.

While the IC scheme is used to reduce MAI, the purpose of interference generation block is to regenerate the interference due to user k by reconstructing the original transmitted signals of one or more users. The new extrinsic information, $L_d[s^k(n)]$, based on the *a priori* means, $E[s^k(n)] = \tanh\{L_d[s^k(n)]/2\}$, and variances, $var[s^k(n)] = 1 - (E[s^k(n)])^2$, is calculated and mapped to suitable constellation points, to form new decision symbols $\hat{s}^k(n)$. The $\hat{s}^k(n)$ symbols are summed to form the MAI signal as

$$\hat{z}(n) = \sum_{k=1}^{K} \hat{s}^k(n), \tag{27}$$

and fed to the FB filter. As the IC operation progresses, the estimates of the MAI improves and, in later stages of the iterative scheme, the data estimates of all the users have been obtained.

4. SIMULATION RESULTS

4.1 Simulation Conditions

In this section, simulations results of HDFE-IDMA and FDFE-IDMA schemes are presented and compared with those of FDE-IDMA and multi-carrier OFDM-IDMA schemes, with CP and ZP techniques **,Guo, et al., 2008.** All of the schemes use the same encoding scheme, a rate 1/2 convolutional code with generator polynomial $(23, 35)_8$, followed by repetition code with length $N_s = 6$. The length of the transmitted block for each user is 256 with four active users. The number of iterations is 3 for all the schemes. The interleaved chips after QPSK modulation are linearly superimposed and transmitted over a bandwidth of 4 MHz with equal power allocation and uniform phase distribution. In the considered scenario, the transmitted signals undergo independent dispersive Rayleigh fading channels with an exponential power delay profile and normalized root-mean square delay spread. The channel is assumed to be known and time-invariant. The cyclic extension, ZP and CP, have been set to $CP, ZP \geq Np$.

4.2 BER Performance Comparison

In **Fig.** 5, the BER as a function of the E_b/N_o is presented for the proposed schemes. For comparison, the performance of FDE-IDMA and OFDM-IDMA with CP is also shown. The cyclic extension has been set to 25 and the feedback filter of HDFE has been set to $L + 1$ taps. The performance of HDFE-IDMA clearly outperforms other IDMA structures, including OFDM-IDMA and FDE-IDMA, and approaches the 10^{-4} BER level at high E_b/N_o. The proposed HDFE-IDMA scheme results a gain of about 2 dB at BER=10^{-3}. When compared with the other schemes, the proposed FDFE-IDMA structure yields a gain of about 1.5 dB at BER 10^{-3}. The OFDM-IDMA has similar performance to FDE-IDMA for moderate E_b/N_o.

Figs. 6 and 7 show the performance comparison for different IDMA schemes with different number of active users K. For large active users, the performance decreases since the residual interference levels and the error propagation can be high. However, the FDFE/HDFE is effective in reducing the ISI generated by the dispersive channels. It is also noticed in **Fig. 8** that the first two iterations result a significant improvement, while the improvement of further iterations is reduced and the performance gains associated to the iterative procedure are higher for small K. However, the large K requires the independent processing of ISI and MAI that is carried out in such proposed schemes. This makes the proposed schemes an attractive choice when coding schemes are involved and the structures allow equalization and coding to be done separable.
The performance of OFDM-IDMA and FDE-IDMA with ZP is also drawn in **Fig. 9** and compared with that of HDFE-IDMA and FDFE-IDMA. The proposed structures are clearly outperforms other schemes and results an improvement of about 1 dB at BER 10^{-3}, due to the equalizer's ability. Further, the FDE-IDMA has similar performance to OFDM-IDMA for high E_b/N_o. The improvement in FDFE-IDMA performance can be explained as a result of the iteration process and the improved FB part that is able to remove both precursors and postcursors of ISI. Moreover, the iterative process gradually increases the reliability of the detected symbols and reduces the effects of the error propagation that limits the performance of non-iterative DFE based schemes.

4.3 Complexity Comparison

In this section, the computational complexity, per chip (a QPSK symbol), per user, of the various IDMA schemes is evaluated in **Table 1** in terms of the number of complex multiplications (nCMuls). The nCMul is taken as parameter because it consumes more hardware than addition and other operations. The comparison does not take into account the decoders, despreaders, spreaders and interleavers operations since these operations are identical in both receivers. An example with $K = 4, L = 24,\ it = 3$ and $N = 256$ is also given.
In the OFDM-IDMA scheme, the independent treatment of ISI and MAI reduces the processing cost of MUD. There is approximately a factor of L between the detection cost for TD schemes and that for multicarrier scheme. The IC block has linear complexity in frame length and is independent of L. The FFT costs for one chip $(N \times \log_2 N)/2$ complex multiplications and $(N \times \log_2 N)$ additions/subtractions for N chips. For the OFDM-IDMA scheme, according to the algorithm given in **,Yueqian, 2007** , there are approximately 1120 CMuls, per chip, per user involved in detection process. Since OFDM demodulation is carried out for all users before the iterative detection process, the FFT cost is independent of the user number K, the path number L, and the iteration number. In contrast, there are approximately 67680, 41640 CMuls for the FDE-IDMA and TD-DFE-IDMA, respectively. When compared to OFDM-IDMA, DFE-IDMA has an increased complexity due to the TD filtering operations. Moreover, the FDE-IDMA has a significantly higher complexity than both OFDM-IDMA and DFE-IDMA. Indeed, the filter design for OFDM-IDMA is much less complex than that for other systems.
In the FDFE-IDMA, after an initial FFT to obtain the vector R, at each it, the filters' coefficients require one CMul and two IFFT per block, except for the last iteration that requires only an IFFT. In each block, we have N_d data symbols only, the remaining $(N - N_d)$ are training symbols sent for channel estimation. The overall complexity for FDFE is, $[((N/2\ \log_2 N - N) + N)/N_d - N/N_d]$ and for IC is, $2 \times\ K$. While the inversion of a correlation matrix of size Q in the design of the TD-DFE and HDFE has a complexity of $O(Q^3)$ and $O(Q^2)$, respectively. The HDFE-IDMA results a computation reduction of about one-third when compared with TD-DFE-IDMA. In turn, FDE-IDMA reduces complexity, with respect to HDFE-IDMA, of another 55%-65%. The channel estimation was not considered because these schemes except the TD-

DFE-IDMA need the same estimate of the channel frequency domain response, which can be obtained by known techniques in **Edfors, et al., 1998** and references therein.

However, in the design of the FF and FB filters of FDFE-IDMA, H^2 has to be calculated by channel estimation, while one division and two multiplications are needed for each iteration. The complexity of these turbo structures may vary significantly according to the dispersion of the channel. However, FF and FB filters in FDFE-IDMA have a very simple implementation because no matrix operations are involved and the provided complexity may be negligible for low or moderate dispersion channels.

5. CONCLUSIONS

In this paper, an equalization and IC scheme, HDFE-IC and FDFE-IC, in conjunction with coding have been considered for wideband IDMA systems. In the proposed HDFE-IDMA structure, the signal processing and the FF filter design of the HDFE that operates on blocks of the data are performed entirely in the FD. While in the proposed FDFE-IDMA structure, both the FF and FB filtering operations are performed in the FD, which yields a reduced complexity with respect to existing IDMA receivers. The performance gain of HDFE-IDMA is significant when it is compared with the performance of OFDM-IDMA and SC-FDE-IDMA. Moreover, the integration of FDFE and IC outperforms significantly HDFE-IDMA, OFDM-IDMA and FDE-IDMA. However, the application of FD techniques makes SC-IDMA with DFE a potentially valuable alternative to multicarrier systems and a variety of issues remain to be explored in future research.

6. References

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List of Abbreviations

BER: bit error rate
CP: cyclic prefixing
FF: feedforward
FB: feedback
FDFE: frequency decision-feedback equalization
FFTs: Fast Fourier Transforms

FDE: frequency domain equalization
HDFE: hybrid decision feedback equalization
IC: interference cancellation
ISI: intersymbol interference
IBDFE: iterative block decision feedback equalization
IFFT: inverse Fast Fourier Transform
LE: linear equalization
LLRs: log-likelihood ratios
MUD: multiuser detection
MMSE: minimum mean square error
MAI: multiple access interference
nCMuls: number of complex multiplications
OFDM: orthogonal frequency division multiplexing
PIC: parallel interference cancellation
QPSK: quadrature phase shift key
SC-IDMA: single-carrier interleave division multiple access
TD: time domain
TDE: time domain equalization
ZP: zero padding
ZF: zero forcing

List of Symbols
$c^k(m)$: repetition code
$d^k(n)$: information bits of user k
$\boldsymbol{G}_{FF}(n)$: complex valued FF coefficients in HDFE
$h_p^k(n)$: the channel fading coefficients for the user k
H^k: the FFT of h^k
it: iteration number
J_{MMSE}: the cost function
K: number of active users
L: number of FB filter taps
$L_d\ [s^k(n)]$: *a priori* known information
$L_m[s^k(n)]$: the LLRs for user k
M_w: the average power of the MAI and noise signals
m: time index after coding
n: time index of transmitted bits
N: number of transmitted bits
N_s: spreading factor
N_d: number of data symbols
N_p: number of paths
N_0: noise power
p: path index
$r(n)$: the received signal
R: the received signal in FD
$\hat{s}^k(n)$: tentative feedback decisions
$s^k(n)$: the transmitted signal
S^k: the transmitted signal in FD

$t^k(n)$: the training sequence
$\hat{y}(n)$: the output of HDFE
T: time period
$w(n)$: the additive noise process
W_{FF} : FF filter coefficients in the FD
W_{FB}: FB filter coefficients in the FD
W^H: the N by N FFT matrix
z: the input to the IC block
$\hat{z}\ \ (n)$: the soft feedback detected data
σ^2: variance
$\hat{\sigma}_e^{it}$: disturbance power
Π_k: user-specific interleaver
Π_k^{-1}: dinterleaver for the user k

Table 1. Complexity comparison of the various IDMA schemes.

Structure	nCMuls	nCMuls for considered simulation scenario
OFDM-IDMA	$(N \times \log_2 N)\frac{1}{2} + 8 \times K \times it$	1120
FDE-IDMA	$N \times \log_2 N + N^2 + 8 \times K \times it$	67680
DFE-IDMA	$[(M_{FF} + M_{FB} + M_{FF}^3) + 2 \times K] \times it$	41640
HDFE-IDMA	$[\left(\frac{N}{N_d} \times \log_2 N + M_{FB}\right) + ((2N_p)^2 + 2N + N\log_2 N) + 2 \times K] \times it$	15578
FDFE-IDMA	$[((N/2\ \log_2 N - N) + N)/N_d - N/N_d] \times it + [(3 \times it + 1) \times N] + 2 \times K \times it$	2844

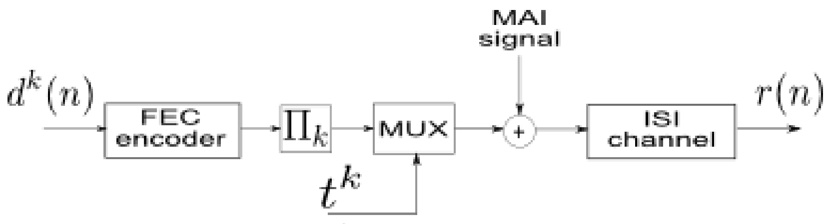

Figure 1. The discrete time block diagram of an IDMA transmitter for user-k.

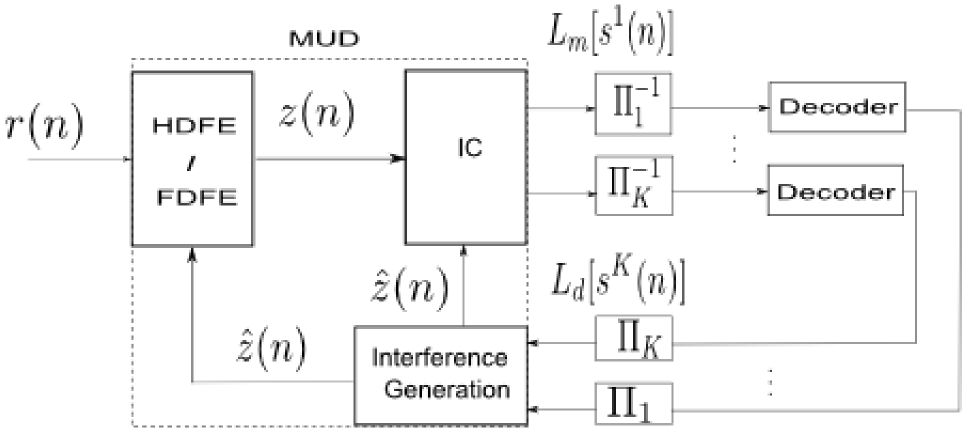

Figure 2. Iterative multiuser detector with FDE for SC-IDMA receiver.

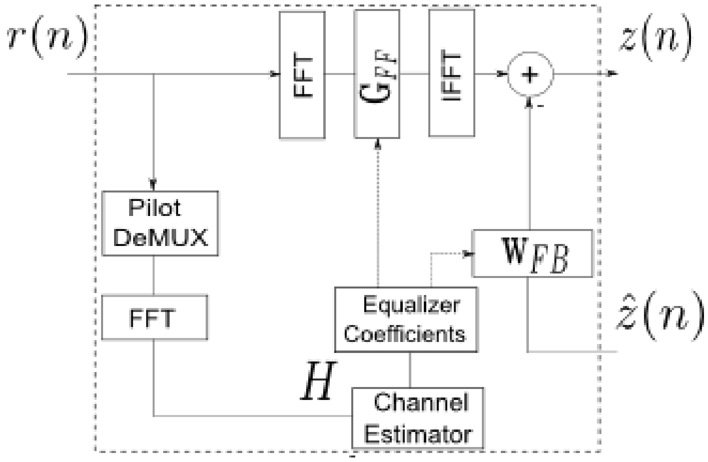

Figure 3. HDFE with FF filter in FD and FB filter in TD.

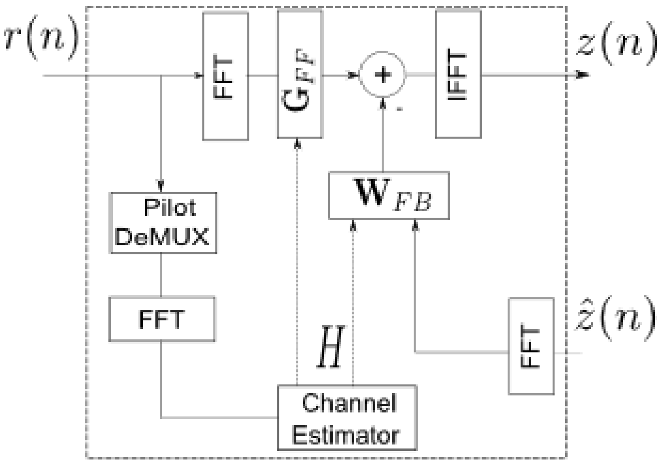

Figure 4. FDFE with FF and FB filters in FD.

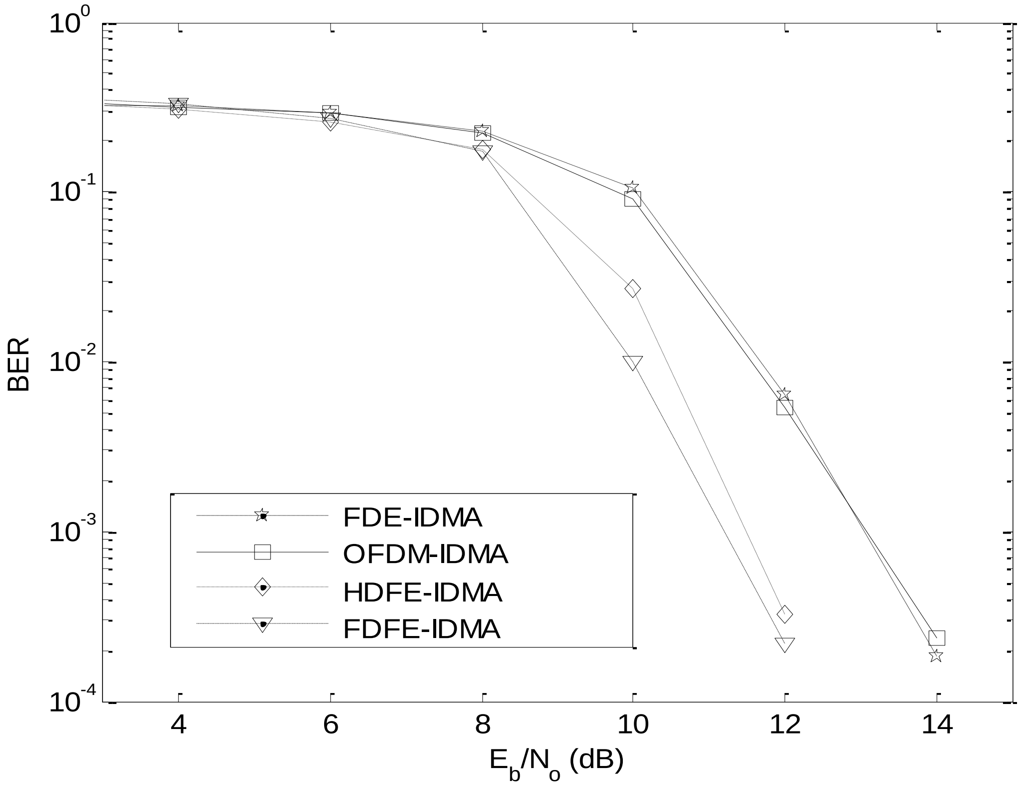

Figure 5. Performance comparison between HDFE-IDMA, FDFE-IDMA and FDE-IDMA, OFDM-IDMA with CP.

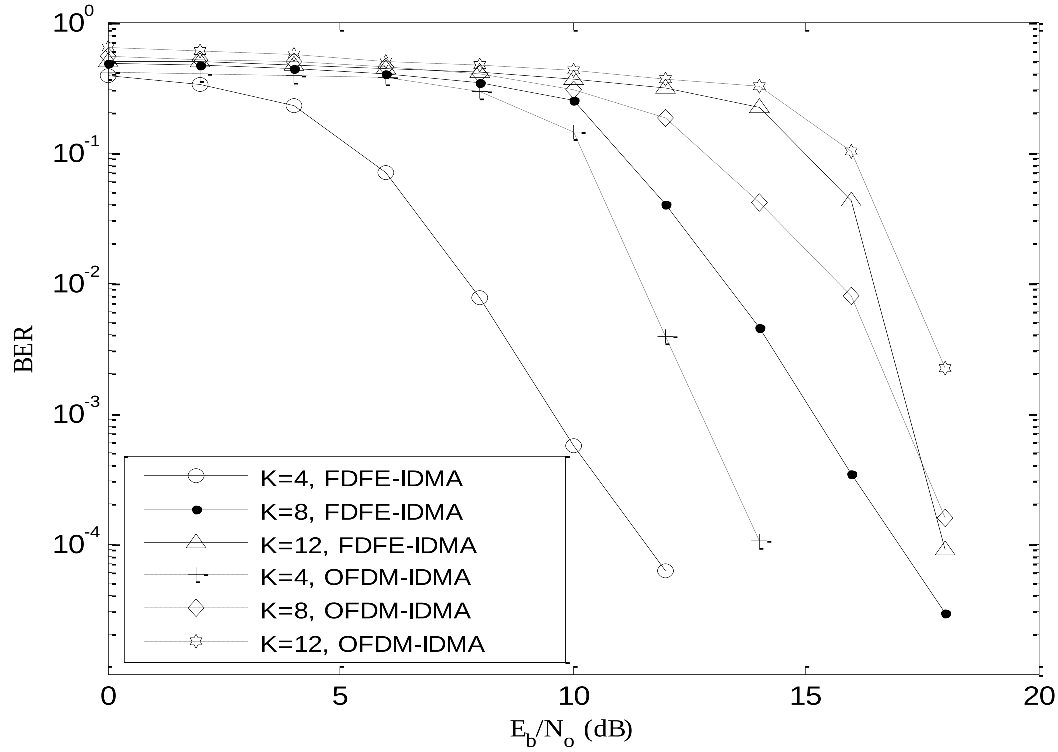

Figure 6. Performance of FDFE-IDMA (solid lines) and OFDM-IDMA (dashed lines) with different number of active users K.

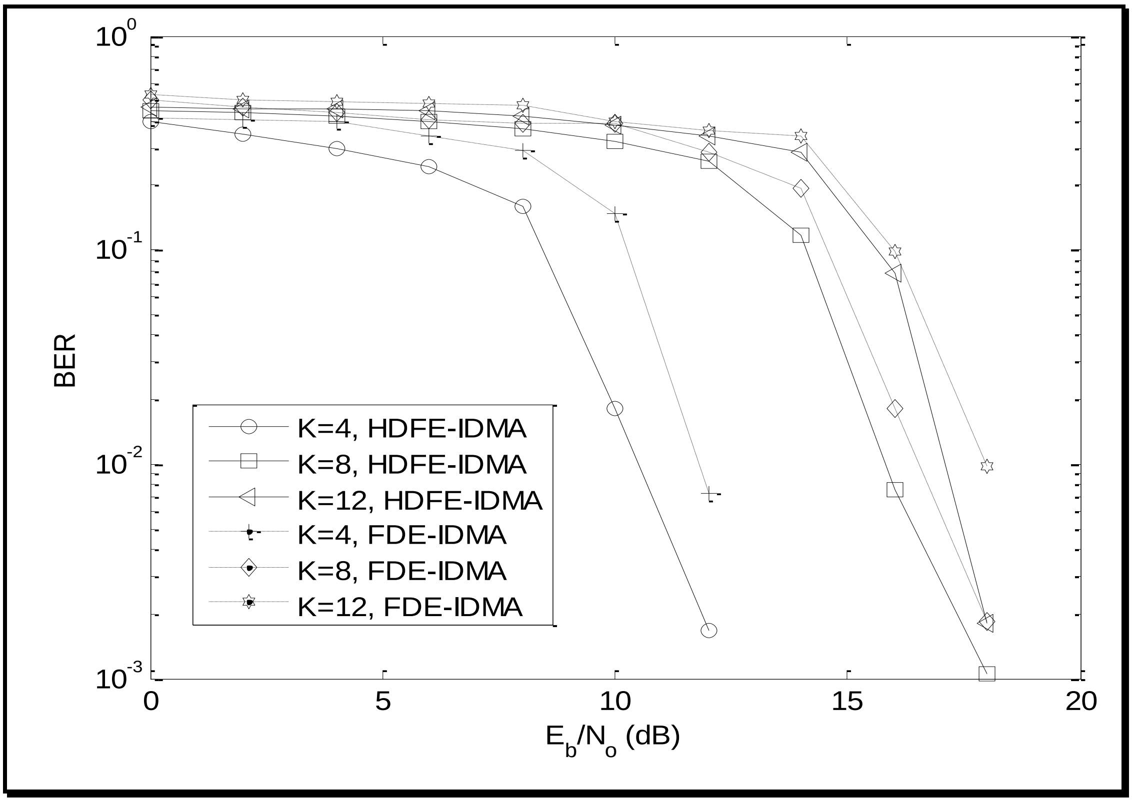

Figure 7. Performance of HDFE-IDMA (solid lines) and FDE-IDMA (dashed lines) with different number of active users K.

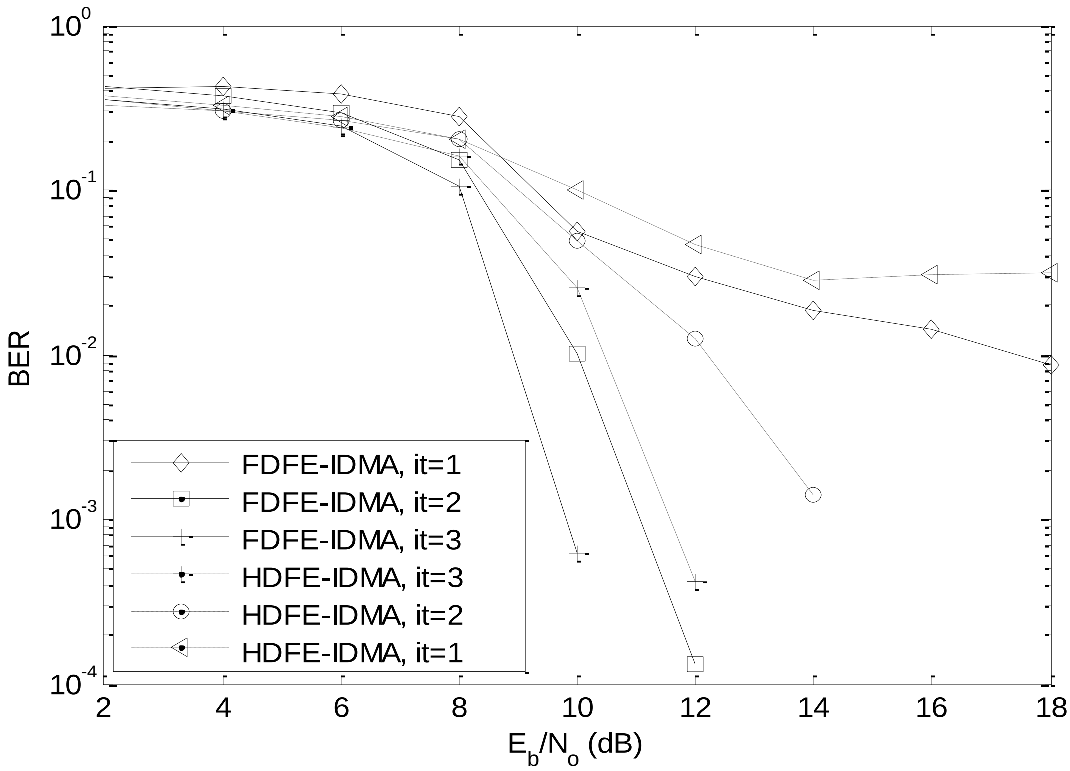

Figure 8. Performance comparison between FDFE-IDMA (solid lines) and HDFE-IDMA (dashed line) with different it number.

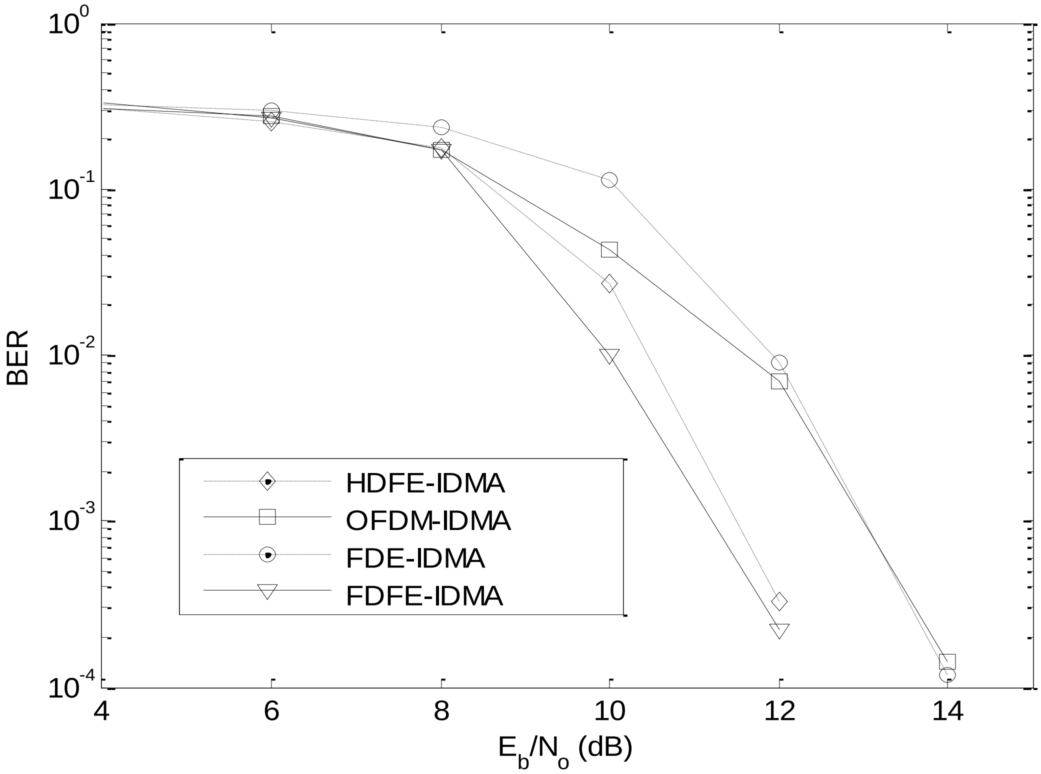

Figure 9. Performance comparison between HDFE-IDMA, FDFE-IDMA and FDE-IDMA, OFDM-IDMA with ZP.