Interleaving Techniques for W-CDMA Linear Equalization Receivers

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***Abstract*—This paper focuses on the use of specific interleaving techniques for use in W-CDMA (Wideband Code Division Multiple Access). The linear equalization algorithm usually performs a matrix inversion on a matrix with a high level of sparseness, and such sparseness shouldn't be compromised with the use of a random interleaver; specific interleaver designs should be employed in order to keep the complexity of the equalization algorithm down to an acceptable level. The used equalizer is based on the linear MMSE (Minimum Mean Square Error) algorithm and is tested using the UMTS (Universal Mobile Telecommunications System) HSDPA (High Speed Downlink Packet Access) standard as a basis, including the reference UMTS environments.**

Keywords- Equalization, MMSE, interleaver, HSDPA.

I. INTRODUCTION

Nowadays increasing need for high data rate wireless communications requires the use of sophisticated transmission and reception systems. Such systems need to be able to cancel out all type of interference such as ISI (Inter Symbolic Interference), MAI (Multiple Access Interference) and the ever-present thermal noise. In order to effectively cancel out most of the interference (the hardest component to get rid of is the thermal noise, due to its random nature), an equalizer needs to be employed. Such equalizer reproduces the deterministic interference present in the system, aided by the knowledge of the channel (via channel estimation techniques [5]), and the spreading & scrambling codes of each physical channel, alongside their relative delays, for CDMA systems. The thermal noise can only be partially compensated, if an equalizer such as the one based on the MMSE method is employed; otherwise it can simply be ignored if the Zero-Forcing method is used. The linear version of these two equalization methods will be used in this paper.

The equalization itself needs to invert a matrix that represents the cross-correlation between all symbols, built with the channel knowledge, delays and codes, as previously described. For normal channel delay spreads, such as the referenced channels for the UMTS, the delay is usually small, within one symbol time. Therefore, the correlation between symbols is kept down to a minimum, and the matrix is very sparse. With the aid of sparse solving methods, the complexity of the matrix inversion can be kept down to reasonable levels.

When a random interleaver at the chip level is introduced, better performance levels are to be expected, since the chips are separated in order to minimize the channel's fading effect. However, such interleaver must be carefully designed, since a random interleaver may induce added cross-correlation between the chips and end with the sparseness level of the inversion matrix, increasing the decoding complexity considerably.

The structure of the paper is as follows. In section II, the common MMSE receiver for W-CDMA is introduced [1], and the chip-wise structure required for the introduction of an interleaver at the chip level is discussed in section III. The interleaver schemes are boarded in section IV. Simulation results are described in section V, and conclusions are drawn in section VI.

II. MMSE RECEIVERS

A standard model for a DS-CDMA system with K users (assuming 1 user per physical channel) and L propagation paths is considered. The modulated symbols are spread by a Walsh-Hadamard code with length equal to the Spreading Factor (*SF)*.

Assuming that the transmitted signal on a given antenna is of the form

$$\boldsymbol{e}(t)_{tx=1} = \sum_{n=1}^{N}\sum_{k=1}^{K} \boldsymbol{A}_{k,tx}\boldsymbol{b}_{k,tx}^{(n)}\boldsymbol{s}_k(t-nT), \quad (1)$$

where N is the number of received symbols, $\boldsymbol{A}_{k,tx}=\sqrt{E_k}$, E_k is the energy per symbol, $\boldsymbol{b}_{k,tx}^{(n)}$ is the n-th transmitted data symbol of user k and transmit antenna tx, $\mathbf{s}_\text{k}$(t) is the k-th user's signature signal (equal for all antennas) and T denotes the symbol interval.

The received signals of a MIMO system with N_{TX} transmit and N_{RX} receive antennas, on one of the receiver's antennas can be expressed as:

$$\boldsymbol{r}_{v_{rx=1}}(t)=\sum_{tx=1}^{N_{TX}}\boldsymbol{e}_{tx}(t)*\boldsymbol{c}_{tx,rx}(t)+\boldsymbol{n}(t) \tag{2}$$

where ***n(t)*** is a complex zero-mean AWGN (Additive White Gaussian Noise) with variance σ^2, $\boldsymbol{c}_{tx,rx}(t)=\sum_{l=1}^{L}\boldsymbol{c}_{tx,rx,l}^{(n)}\delta(t-\tau_l)$ is the impulse response of the radio link between the antenna *tx* and *rx* (assumed equal for all users using this link), $\boldsymbol{c}_{\text{tx,rx,l}}$ is the complex attenuation factor of the *l*-th path of the link, τ_l is the propagation delay (assumed equal for all antennas) and * denotes convolution. The received signal on can also be expressed as:

$$\boldsymbol{r}_{v_{rx=1}}(t)=\sum_{n=1}^{N}\sum_{tx=1}^{N_{TX}}\sum_{k=1}^{K}\sum_{l=1}^{L}\boldsymbol{A}_{k,tx}\boldsymbol{b}_{k,tx}^{(n)}\boldsymbol{c}_{tx,rx}(t)\boldsymbol{s}_k(t-nT-\tau_l)+\boldsymbol{n}(t) \tag{3}$$

Using matrix algebra, the received signal can be represented as

$$\boldsymbol{r}_v=\boldsymbol{SCAb}+\boldsymbol{n}, \tag{4}$$

where ***S***, ***C*** and ***A*** are the spreading, channel and amplitude matrices respectively. The structure of the matrices is explained in detail in [1].

Vector ***b*** represents the information symbols. It has length $(K\cdot N_{TX}\cdot N)$, and has the following structure

$$\boldsymbol{b}=\left[\mathrm{b}_{1,1,1},\ldots,\mathrm{b}_{\mathrm{N_{TX}},1,1},\ldots,\mathrm{b}_{1,\mathrm{K},1},\ldots,\mathrm{b}_{\mathrm{N_{TX}},\mathrm{K},1},\ldots,\mathrm{b}_{\mathrm{N_{TX}},\mathrm{K},\mathrm{N}}\right]^T. \tag{5}$$

Note that the bits of each transmit antenna are grouped together in the first level, and the bits of other interferers in the second level. This is to guarantee that the resulting matrix to be inverted has all its non-zeros values as close to the diagonal as possible. Also note that there is usually a higher correlation between bits from different antennas using the same spreading code, than between bits with different spreading codes.

The *n* vector is a $(N\cdot SF\cdot N_{RX}+N_{RX}\cdot\psi_{MAX})$ vector with noise components to be added to the received vector r_v, which is partitioned by N_{RX} antennas,

$$\boldsymbol{r}_v=\left[\boldsymbol{r}_{1,1,1},\ldots,\boldsymbol{r}_{1,SF,1},\ldots,\boldsymbol{r}_{N,1,1},\ldots,\boldsymbol{r}_{N,SF+\psi_{MAX},1},\ldots,\boldsymbol{r}_{N,1,N_{RX}},\ldots,\boldsymbol{r}_{N,SF+\psi_{MAX},N_{RX}}\right]^T. \tag{6}$$

Equalization-based receivers compensate for all effects that the symbols are subject to in the transmission chain, namely the MAI (Multiple Access Interference), ISI (Inter-Symbolic Interference) and the channel effect. Thus being, only the thermal noise cannot be compensated for, since only its power level can be effectively estimated.

The equalization receiver used as basis in this works makes use of the MMSE algorithm, as is based on the Matched Filter output,

$$\boldsymbol{y}_{MF}=(\boldsymbol{SCA})^H\boldsymbol{r}_v \tag{7}$$

The MMSE estimate aims to minimize $E\left(\left|\boldsymbol{b}-\hat{\boldsymbol{b}}\right|^2\right)$, where

$$\hat{\boldsymbol{b}}=\boldsymbol{L}^H\boldsymbol{r}_v \tag{8}$$

is the MMSE estimate. From [2], the EM (Equalization Matrix) includes the estimated noise power σ^2, and is represented by

$$\boldsymbol{E}_{M,MMSE}=\boldsymbol{R}+\sigma^2\boldsymbol{I}. \tag{9}$$

$$\boldsymbol{R}=AC^HS^HSCA \tag{10}$$

The MMSE estimate is thus

$$\boldsymbol{y}_{MMSE}=\left(\boldsymbol{E}_{M,MMSE}\right)^{-1}\boldsymbol{y}_{MF}, \tag{11}$$

with

$$\boldsymbol{L}=\boldsymbol{SCA}\cdot\left(\boldsymbol{R}+\sigma^2\boldsymbol{I}\right)^{-1}. \tag{12}$$

III. Chipwise Structure

The previous section described the MMSE algorithm (or the ZF, if we take $\sigma^2=0$) as it is commonly referred to. If chip interleaving is to be used, and in order to keep the described matrix structure, the following adjustments can be made

$$\boldsymbol{r}_v=\boldsymbol{S'CAb'}+\boldsymbol{n}, \tag{13}$$

where the symbols portrayed by vector ***b*** were replaced with

$$\boldsymbol{b}'=\boldsymbol{S}_{outer}\boldsymbol{b}, \tag{14}$$

i.e., the spreaded & scrambled version of ***b***. This being, the symbols to be estimated are the chip-wise sum of all physical channels/all users.

The $\boldsymbol{S}_{outer}$, representing the spreading and scrambling matrix, transforms the symbol vector ***b*** to a spreaded & scrambled vector ***b'***, where all the physical channels are first spreaded & scrambled, and then added together. Each symbol to be decoded is thus the sum of each chip from all physical channels. $\boldsymbol{S}_{outer}$ is a $(SF\cdot N\cdot N_{TX})\times(K\cdot N\cdot N_{TX})$ matrix. It is composed of $\boldsymbol{S}_{outer}=\left[\boldsymbol{S}_{\varepsilon,1},\ldots,\boldsymbol{S}_{\varepsilon,\mathrm{N}}\right]$, with

$$\boldsymbol{S}_{\varepsilon,\mathrm{n}}=\begin{bmatrix}0_{(\mathrm{SF}\cdot N_{TX}\cdot(n-1))\times(K\cdot N_{TX})}\\ \boldsymbol{S}_{\mathrm{n}}^{\mathrm{L}}\\ 0_{(\mathrm{SF}\cdot N_{TX}\cdot(N-n))\times(K\cdot N_{TX})}\end{bmatrix}.$$

Each $\boldsymbol{S}_{\mathrm{n}}^{\mathrm{L}}$ matrix is composed of (with the empty areas being filled with zeros)

$$\boldsymbol{S}_n^L=\begin{bmatrix}
\boldsymbol{S}_{1,1,1,n} & & & \boldsymbol{S}_{1,2,1,n} & & & \cdots & \boldsymbol{S}_{1,K,1,n} & & \\
 & \ddots & & & \ddots & & \cdots & & \ddots & \\
 & & \boldsymbol{S}_{N_{TX},1,1,n} & & & \boldsymbol{S}_{N_{TX},2,1,n} & \cdots & & & \boldsymbol{S}_{N_{TX},K,1,n} \\
\boldsymbol{S}_{1,1,2,n} & & & \boldsymbol{S}_{1,2,2,n} & & & \cdots & \boldsymbol{S}_{1,K,2,n} & & \\
 & \ddots & & & \ddots & & \cdots & & \ddots & \\
 & & \boldsymbol{S}_{N_{TX},1,2,n} & & & \boldsymbol{S}_{N_{TX},2,2,n} & \cdots & & & \boldsymbol{S}_{N_{TX},K,2,n} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\boldsymbol{S}_{1,1,SF,n} & & & \boldsymbol{S}_{1,2,SF,n} & & & \cdots & \boldsymbol{S}_{1,K,SF,n} & & \\
 & \ddots & & & \ddots & & \cdots & & \ddots & \\
 & & \boldsymbol{S}_{N_{TX},1,SF,n} & & & \boldsymbol{S}_{N_{TX},2,SF,n} & \cdots & & & \boldsymbol{S}_{N_{TX},K,SF,n}
\end{bmatrix}.$$

The interleaving is applied to the rows of the $\boldsymbol{S}_{outer}$ matrix, according to a specific algorithm (since the interleaving will affect the structure of the equalization matrix, the interleaving algorithm must be deterministic in order to predict the structure of the EM and to employ specific decoding algorithms to such matrix, in order to reduce complexity as much as possible). The next section will discuss different interleaver algorithms.

The inner spreading matrix ***S'***, simply accounts for the multipath delays. This could be included in the channel matrix ***C***, but it wasn't in order to keep ***C*** similar to that of the normal MMSE receiver. Therefore, the inner spreading matrix ***S'*** has dimensions $(SF\cdot N\cdot N_{RX}+\psi_{MAX}\cdot N_{RX})\times(L\cdot N\cdot SF\cdot N_{RX})$, and is similar to the ***S*** matrix of the normal MMSE receiver, the only difference being that all entries are "1"s (the spreading factor is considered to be unitary). The channel matrix $\boldsymbol{C}$ and amplitude matrix $\boldsymbol{A}$ structures remain the same - note that there are now SF$\times N$ symbols, instead of only $K\times N$ symbols. Since the different users were aggregated, all matrices account for only one user, with SF$\times N$ symbols**.**

The whole MMSE processing is very similar to the normal case with slight modifications; since the symbols to be estimated no longer have unit power (since all of the chips pertaining to different users using the same antenna are summed), the estimate is given by

$$\boldsymbol{y}_{MMSE} = \hat{\boldsymbol{b}} = \left(\boldsymbol{H}^H\boldsymbol{H} + \sigma^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^H\boldsymbol{r}\,, \tag{15}$$

where

$$\boldsymbol{H} = \boldsymbol{S'}\times\boldsymbol{C}\times\boldsymbol{A}\times\boldsymbol{S}_{outer}\,. \tag{16}$$

The spreaded MF response is given by

$$\boldsymbol{y}_{MF} = \left(\boldsymbol{S'CAS}_{outer}\right)^H \boldsymbol{r}_v\,, \tag{17}$$

where $\boldsymbol{S'}$ is used instead of $\boldsymbol{S}$. The intermediate matrix $\boldsymbol{R}$ is now given by

$$\boldsymbol{R} = \boldsymbol{S}_{outer}^{\boldsymbol{H}}\times\boldsymbol{A}\times\boldsymbol{C}^{\boldsymbol{H}}\times\boldsymbol{S'}^{\boldsymbol{H}}\times\boldsymbol{S'}\times\boldsymbol{C}\times\boldsymbol{A}\times\boldsymbol{S}_{outer}\,, \tag{18}$$

and

$$\boldsymbol{E}_{M,MMSE} = \boldsymbol{R} + \sigma^2\boldsymbol{I}\,, \tag{19}$$

followed by

$$\boldsymbol{y}_{MMSE} = \left(\boldsymbol{E}_{M,MMSE}\right)^{-1}\cdot\boldsymbol{y}_{MF}\,. \tag{20}$$

IV. Interleaving Algorithms

Different interleaving algorithms were used in this work. To start off, the random interleaver was employed, serving as a reference to all others. The random permutation of lines of the $\boldsymbol{S}_{outer}$ matrix practically ends with the sparseness of the EM, and thus this is the setting requiring the most complexity.

Other considered interleaving schemes were the block interleaver, the Diagonal Parallel Lines (DPL) interleaver, a mixture of the block and DPL interleaver (BDPL) and the zigzag interleaver. All cases were compared to the situation without interleaving.

A. *Random Interleaver*

The simplest type of interleaver merely permutes all lines of the $\boldsymbol{S}_{outer}$ matrix randomly. The effect of this random shuffling makes almost all symbols correlated with each other (Figure 5 - left), increasing the complexity of inverting the matrix dramatically.

B. *Block Interleaver*

The block interleaver uses random interleaving in block sizes of SF^2 lines. It is a partial version of the random interleaver, that preserves the diagonal structure of the $\boldsymbol{S}_{outer}$ (Figure 1 - right) and EM (Figure 5 - right) matrices. Although there is a significant increase of correlation in the EM, it is obvious that the resultant matrix is still sparse, requiring only a bit more solving complexity.

C. *DPL Interleaver*

The DPL interleaver aims to scatter the chips pertaining to each symbol evenly throughout the block, so as to minimize the channel effect. The name DPL comes from the structure that $\boldsymbol{S}_{outer}$ acquires after interleaving (Figure 2 - left). The main advantage of this scheme is that the EM is practically untouched (Figure 6 - left).

D. *BDPL Interleaver*

The BDPL interleaver first applies the block interleaver algorithm, and only afterwards applies the DPL algorithm. The DPL algorithm however, will now consider that a SF equal to SF^2 is used, since that is the equivalent SF size after the block interleaver. Although the $\boldsymbol{S}_{outer}$ is random-like (Figure 2 - right), the EM remains reasonably sparse, and structured (Figure 6 - right).

E. *Zigzag Interleaver*

The zigzag interleaver is essentially the same as the DPL interleaver, but has the $\boldsymbol{S}_{outer}$ matrix in a zigzag manner (Figure 3 - left), so that the channel dispersion effect doesn't affect the EM (the values at the top-right and bottom-left of Figure 6-left are not present anymore). This has the advantage of using the same matrix inversion algorithms that are used for the conventional MMSE scheme.

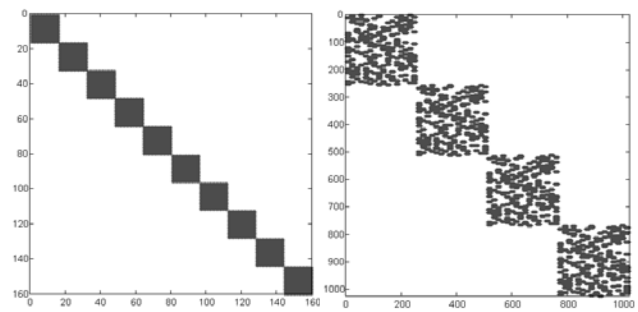

Figure 1 – $\boldsymbol{S}_{outer}$ matrix without interleaving (left) and with block interleaving (right).

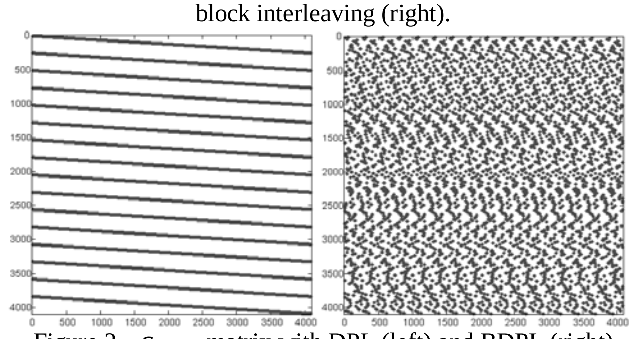

Figure 2– $\boldsymbol{S}_{outer}$ matrix with DPL (left) and BDPL (right) interleaving.

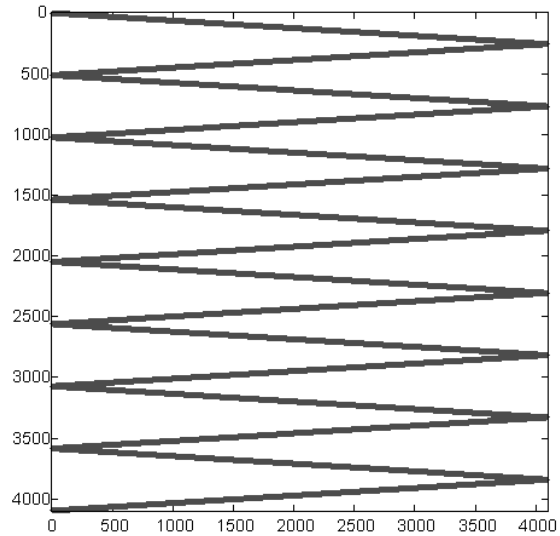

Figure 3– $\boldsymbol{S}_{outer}$ matrix with zigzag interleaving.

The effect of the interleaver on the *EM* plays a very important role. The value of *nz* for each figure represents the number of non-zero elements. In spite of existing specific algorithms for inverting the sparse matrices that have a certain dispositions of their elements, a subjective rule will be created in order to assure fair comparisons – this will be given by $nz^{3/2}$.

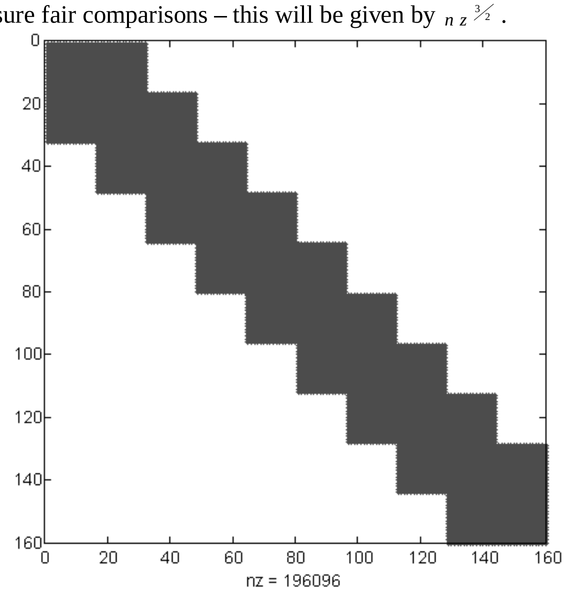

Figure 4– EM with no interleaving/ zigzag.

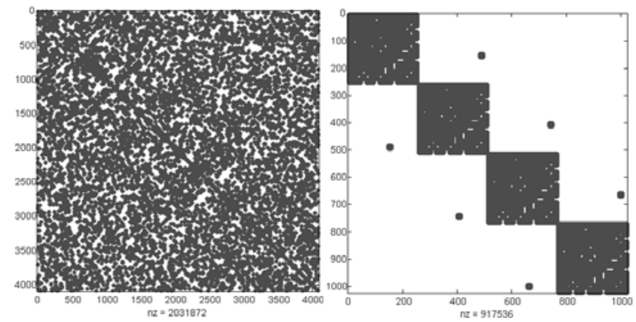

Figure 5– EM with random (left) and block (right) interleaving.

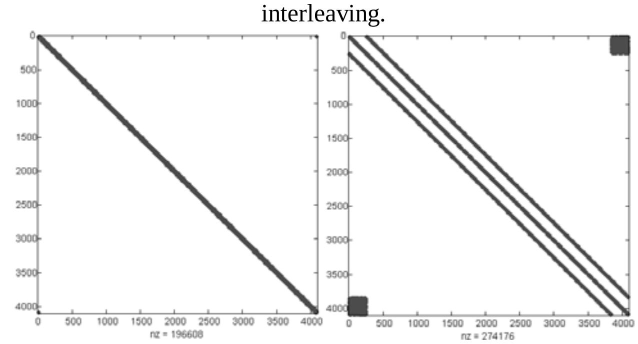

Figure 6– EM with DPL (left) and BDPL (right) interleaving.

Table 1 – Complexity of the different interleavers.

Interleaving	Complexity	Relative Values
None	86.836.658	1,0
Zigzag	86.836.658	1,0
DPL	87.176.972	1,0
BDPL	143.563.539	1,7
Block	878.890.296	10,1
Random	2.896.306.497	33,4

V. RESULTS

Results are portrayed for the SISO (Single Input, Single Output) system, using the Pedestrian A and Vehicular A channels [3]. A block size of 512 bits was considered, using QPSK modulation. Results will be shown for different ratios of Doppler frequency (Df) to transport block size (TBs).

The different interleaving schemes were considered for simulation, using the MMSE equalization algorithm. It can be seen that the interleaving plays a very important role in the BER performance, yielding gains in the order of 2-3dB. From the results, it can be seen that the block interleaver isn't very effective. The BDPL yields results very similar to those of the random interleaver, but the best interleaving schemes are the DPL and zigzag (the interleavers requiring the least complexity and that are deterministic). As expected, the DPL interleaver is the best interleaving scheme performance-wise, since it spreads the chips evenly throughout the whole block – the zigzag interleaver is only marginally inferior, since only half the chips are spread throughout the block. However, in terms of complexity and performance results, the zigzag interleaver should be preferred, if the same algorithm for solving the EM is to be used.

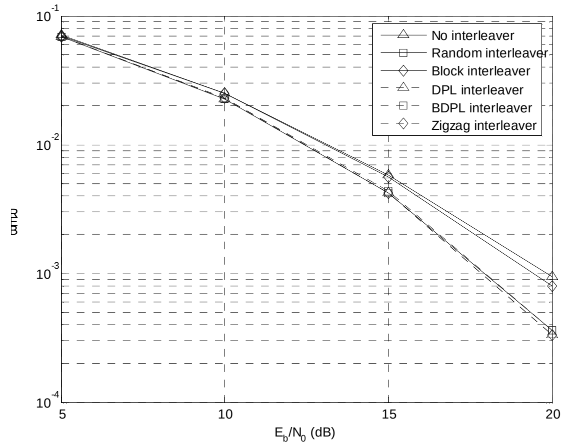

Figure 7– Interleaver Results, Pedestrian A channel, SISO, fully loaded, Df/TBs=0,36 Hz/bit.

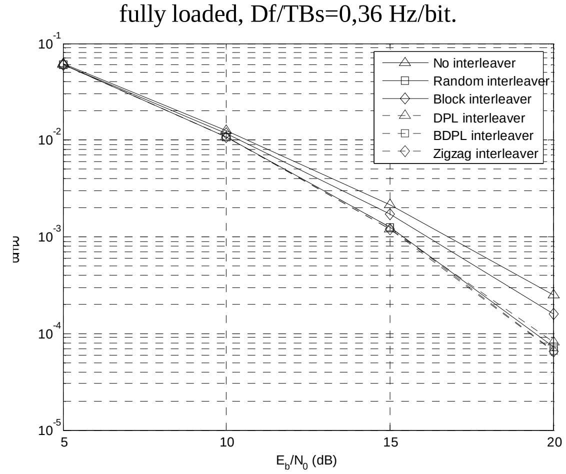

Figure 8– Interleaver Results, Vehicular A channel, SISO, fully loaded, Df/TBs=0,36 Hz/bit.

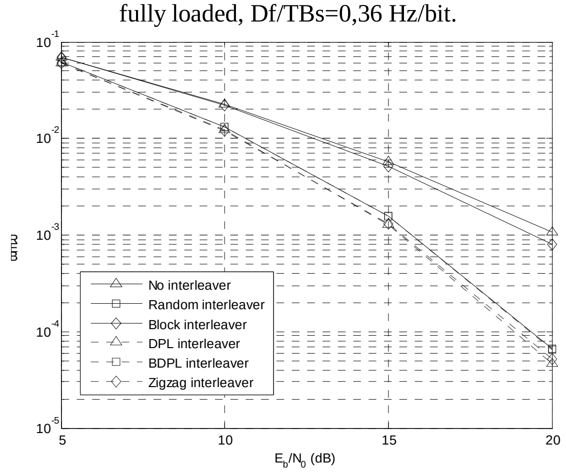

Figure 9– Interleaver Results, Pedestrian A channel, SISO, fully loaded, Df/TBs=1,81 Hz/bit.

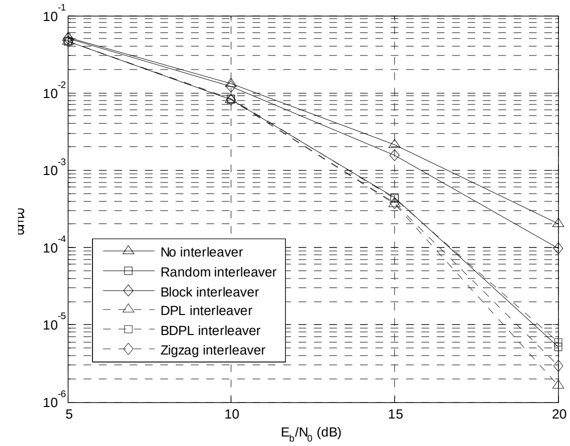

Figure 10– Interleaver Results, Vehicular A channel, SISO, fully loaded, Df/TBs=1,81 Hz/bit.

VI. CONCLUSIONS

In this paper, the MMSE-based receiver algorithm was used with different interleaving schemes. Since interleaving of the symbols is fundamental for a realistic channel environment, some form of interleaving had to be found for the MMSE-based equalizer, without raising de decoding complexity to a high level. With the deterministic interleaving schemes exploited in this work, specifically the zigzag interleaver, the complexity of the decoding algorithm is essentially the same (the complexity of the interleaver itself is negligible), and all the advantages of using an interleaver are exploited.

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