On SC/FDE Block Transmission with Reduced Cyclic Prefix Assistance

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Abstract - For conventional CP-assisted (Cyclic Prefix) SC/FDE implementations (Single- Carrier/Frequency-Domain Equalization), as well as for OFDM implementations (Orthogonal Frequency Division Multiplexing), the CP length is known to be selected on the basis of the expected maximum delay spread. Next, the data block size can be chosen to be large enough to minimize the CP overhead, yet small enough to make the channel variation over the block negligible.

This paper considers the possibility of reducing the overall CP assistance, when transmitting sequences of SC blocks, while avoiding an excessively long FFT block for FDE purposes and keeping good performances through a moderate increase of the FDE receiver complexity. Firstly, we present an algorithm for a Decision-Directed Correction (DDC) of the FDE inputs when the CP is not long enough to cope with the time-dispersive channel effects. The resulting FDE performance is then evaluated in worst-case (CP-free) conditions, and the impact of previous decisions which are not error-free is shown to be rather small.

In the following, we present and evaluate a novel class of reduced-CP SC/FDE schemes, which takes advantage of the DDC algorithm for replacing ”useless” CP redundancy by fully useful channel coding redundancy: highly power/bandwidth efficient block transmission schemes, especially recommendable for both strongly time-dispersive and time-varying channel conditions, are then achieved.

I. Introduction

SC (Single Carrier) modulations are known to be suitable for CP-assisted (Cyclic Prefix) block transmission within broadband wireless systems, since a low-complexity, linear FDE (Frequency-Domain Equalization) technique, involving simple FFT (Fast Fourier Transform) computations, can then be employed to solve the severe ISI problem [1]. As with current OFDM-based (Orthogonal Frequency Division Multiplexing) schemes, the CP length is long enough to cope with the maximum relative channel delay. Therefore, in what concerns the useful part of each received burst, any interblock interference (IBI) is avoided; moreover, the linear convolutions, in the time domain, which are inherent to the time-dispersive channels, become equivalent to circular convolutions, corresponding to multiplications in the frequency domain. In recent papers [3], [4], [5], we considered both an OFDM option and an SC/FDE option for broadband wireless communications. These papers provided overall comparisons of the two options, with the help of selected performance results, which were used to support the suggestion of a mixed solution for future broadband systems: an OFDM option for the downlink and an SC/FDE option for the uplink. Especially when space diversity is adopted in the BS (Base Station) but not in the MT (Mobile Terminal), the ”implementation charge” becomes concentrated at the BS (where increased power consumption and cost are not so critical), concerning both the signal processing effort and, due to the strong envelope fluctuation of OFDM signals, the power amplification difficulties.

For conventional CP-assisted block transmission implementations, either MC-based (Multi-Carrier), or SC-based, the CP length is selected on the basis of the expected maximum delay spread, so as to ensure that it is always greater than the channel memory order. Next, the data block size can be selected to be large enough to make the channel variation over the block negligible. Since the use of a cyclic prefix reduces both the spectral efficiency and the power efficiency of block transmission schemes, several approaches have been considered to alleviate this problem, mainly in the MC case, i.e., for DMT/OFDM applications (see, e.g. [6] and the references therein). Specifically for the SC/FDE case, well-known approaches may be considered for block transmission with no cyclic prefix, namely resorting to ”overlap-save”, frequency-domain, linear signal processing methods [7]. However, besides an extra complexity, these methods require FFT block lengths much longer than the maximum delay spread, so as to avoid significant performance degradations.

In this paper, we consider the possibility of reducing the overall CP assistance, when transmitting sequences of SC blocks, while avoiding an excessively long FFT block for FDE purposes. Firstly, we present, in sec. II, an algorithm for a Decision-Directed Correction (DDC) of the FDE inputs when the CP length is not long enough to cope with the time-dispersive channel effects; the resulting FDE performance is then evaluated, under the impact of previous decisions which are not error-free.

In Sec. III, we present and evaluate a novel class of reduced-CP SC/FDE schemes, which takes advantage of the DDC algorithm for replacing ”useless” CP redundancy by fully useful channel coding redundancy, having in mind block transmission applications for both strongly time-dispersive and time-varying channel conditions.

Sec. IV concludes the paper with the relevant conclusions and some complementary remarks.

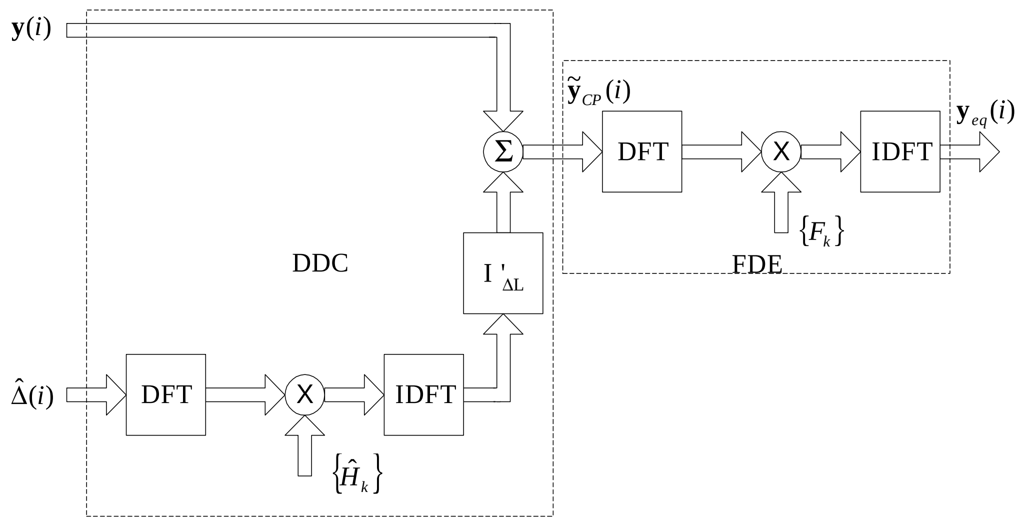

Fig. 1. DDC-FDE receiver for SC-based block transmission with reduced CP assistance.

II. DDC-FDE Scheme for SC-based Block Transmission with Reduced Cyclic Prefix

A. Reduced-CP Block Transmission Issues

For a length-L CIR (Channel Impulse Response), let us consider the transmission of length-N SC-based data blocks $\mathbf{s}(i) = [s_0^{(i)}, s_1^{(i)}, \ldots, s_{N-1}^{(i)}]^T$ ($s_n^{(i)}$ symbol coefficients taken from, e.g., a Quaternary Phase Shift Keying alphabet), with $N > L$. Whenever a length-L CP is appended to each data block, the length-N ith useful received block can be represented by

$$\mathbf{y}_{CP}(i) = \mathbf{H}\mathbf{s}(i) + \mathbf{n}(i), \tag{1}$$

where $\mathbf{n}(i) = [n_0^{(i)}, n_1^{(i)}, \ldots, n_{N-1}^{(i)}]^T$ is the ith received noise vector and $\mathbf{H}$ is the $N \times N$ circulant matrix which describes the channel effects. The entries of this square matrix, given by $h_{j,k} = h_{(j-k)\ mod\ N}$, are related to the length-L CIR ($h_n = 0$ for $n = L+1, L+2, \ldots, N-1$).

When a shortened, length-L_R, CP ($0 \leq L_R < L, N + L_R \geq 2L$) replaces the full-length CP, the initial portion, with $\Delta L = L - L_R$ samples, of each received block will differ from the corresponding initial portion under full-length CP, unless

$$\Delta s_j^{(i)} = s_j^{(i)} - s_{j+L_R}^{(i-1)}, \ \ j = N-L, N-L+1, \ldots, N-L_R-1, \tag{2}$$

is equal to zero. The insufficient CP leads to some IBI and also to an imperfect circular convolution regarding the channel impact on the data block contents.

Obviously, when using $\mathbf{y}(i)$ to denote the new length-N received block, $\mathbf{y}_{CP}(i) - \mathbf{y}(i)$ will depend on $\Delta s_j^{(i)}, j = N - L, \ldots, N - L_R - 1$. It can be shown that

$$\mathbf{y}_{CP}(i) - \mathbf{y}(i) = \mathbf{I}'_{\Delta L}\mathbf{H}\boldsymbol{\Delta}(i), \tag{3}$$

where

$$\mathbf{I}'_{\Delta L} = \mathbf{diag}[\underbrace{1, 1, \ldots, 1}_{\Delta L}, \underbrace{0, 0, \ldots, 0}_{N-\Delta L}] \tag{4}$$

and

$$\boldsymbol{\Delta}(i) = [\underbrace{0, 0, \ldots, 0}_{N-L}, \underbrace{\Delta s_{N-L}^{(i)}, \ldots, \Delta s_{N-L_R-1}^{(i)}}_{\Delta L}, \underbrace{0, 0, \ldots, 0}_{L_R}]^T. \tag{5}$$

B. Algorithm for Decision-Directed Correction of the Equalizer Inputs

Let us consider again the transmission of a length-N SC-based block i with a length-L_R, shortened CP ($0 \leq L_R < L, N + L_R \geq 2L$).

If a perfect a priori knowledge of the ΔL pairs $(s_j^{(i)}, s_{j+L_R}^{(i-1)}), j = N-L, \ldots, N-L_R-1$, could be assumed, it should be possible, having in mind (3), to "correct" the received vector $\mathbf{y}(i)$, by replacing it by the appropriate vector $\mathbf{y}_{CP}(i)$ prior to frequency-domain equalization. When an estimate of those ΔL pairs (i.e., an estimate $\widehat{\boldsymbol{\Delta}}(i)$ of $\boldsymbol{\Delta}(i)$) is available, a Decision-Directed Correction (DDC) of $\mathbf{y}(i)$ can be carried out, so as to obtain a suitable approximation to $\mathbf{y}_{CP}(i)$:

$$\tilde{\mathbf{y}}_{CP}(i) = \mathbf{y}(i) + \mathbf{I}'_{\Delta L}\mathbf{H}\widehat{\boldsymbol{\Delta}}(i) = $$
$$= \mathbf{y}(i) + \mathbf{I}'_{\Delta L}\mathbf{F}^{-1}\mathbf{diag}[\hat{H}_0, \hat{H}_1, \ldots, \hat{H}_{N-1}]\mathbf{F}\widehat{\boldsymbol{\Delta}}(i) \tag{6}$$

where $\mathbf{F}$ and $\mathbf{F}^{-1}$ denote a DFT matrix and an IDFT matrix, respectively, and $[\hat{H}_0, \hat{H}_1, \ldots, \hat{H}_{N-1}]^T$ is the estimated CFR (Channel Frequency Response) vector, DFT of the CIR vector $[\hat{h}_0, \hat{h}_1, \ldots, \hat{h}_{N-1}]^T$.

Therefore, a low-complexity algorithm for obtaining $\tilde{\mathbf{y}}_{CP}(i)$ from the received block $\mathbf{y}(i)$, through the use of the symbol estimates $\hat{s}_j^{(i)}$ and $\hat{s}_{j+L_R}^{(i-1)}$, $j = N-L, \ldots, N-L_R-1$, is as follows:

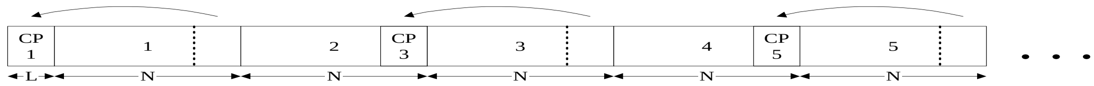

Fig. 2. Simple reduced-CP block transmission scheme.

a) Define the vector estimate

$$\widehat{\boldsymbol{\Delta}}(i) = [\underbrace{0,0,\ldots,0}_{N-L}, \underbrace{\widehat{\Delta s}^{(i)}_{N-L},\ldots,\widehat{\Delta s}^{(i)}_{N-L_R-1}}_{\Delta L}, \underbrace{0,0,\ldots,0}_{L_R}]^T \tag{7}$$

($\widehat{\Delta s}^{(i)}_j = \hat{s}^{(i)}_j - \hat{s}^{(i-1)}_{j+L_R}$).

b) Compute the DFT of the vector estimate $\widehat{\boldsymbol{\Delta}}(i)$, so as to obtain a frequency-domain vector $[\hat{\Delta}^{(i)}_0, \hat{\Delta}^{(i)}_1, \ldots, \hat{\Delta}^{(i)}_{N-1}]^T$.

c) Obtain the corresponding frequency-domain vector at the channel output $[\hat{\Delta}^{(i)}_0 \hat{H}_0, \hat{\Delta}^{(i)}_1 \hat{H}_1, \ldots, \hat{\Delta}^{(i)}_{N-1} \hat{H}_{N-1}]^T$, using a CFR estimate.

d) Compute the IDFT of the frequency-domain vector obtained in c).

e) Retain the initial ΔL components of the vector computed in d), and then add them to the initial ΔL components of $\mathbf{y}(i)$, so as to obtain the vector $\tilde{\mathbf{y}}_{CP}(i)$ which plays the role of $\mathbf{y}_{CP}(i)$ in the subsequent FDE procedures.

The DDC scheme described above can easily cooperate with a conventional, linear FDE scheme, as shown in the receiver structure of Fig. 1. The FDE coefficients can be given by

$$F_k = \hat{H}^*_k / (\hat{\alpha} + |\hat{H}_k|^2), \tag{8}$$

where $\alpha = \sigma_n^2/\sigma_s^2$ (with σ_n^2 and σ_s^2 denoting the variance of noise and data symbols, respectively), provided that widely used linear FDE/MMSE (Minimum Mean-Squared Error) results are adopted. The complexity of the DDC scheme is obviously comparable (a bit lower) to that of the conventional FDE scheme, regardless of the values adopted for N,L and $L_R < L$, with $N + L_R \geq 2L$. A block transmission involving ”CP-free” blocks ($L_R = 0$) is just one of the possibilities, which means ”worst-case” conditions for DDC-FDE operation. Especially in this case, a poor $\hat{\Delta}(i)$ estimate can lead to some degradation of the equalization performance; it should be mentioned that the degraded DDC-FDE outputs, which are not uniformly distributed across the FFT window, become typically more significant for the last L symbols.

A simple way of achieving a reduced-CP block transmission, which allows a very simple computation of each required $\widehat{\Delta}(i)$ vector, is depicted in Fig. 2. It consists of alternately transmitting length-N blocks with full-length CP and length-$(N-L)$ blocks with no CP at all ($L_R = 0$). The FFT block length for FDE purposes in N for both ”odd” and ”even” blocks. Concerning the odd blocks, a conventional FDE procedure is enough for detection. On the other hand, each length-$(N-L)$ even block i (plus the length-L CP of the odd block $i{+}1$) is submitted to the combined DDC-FDE procedures shown in Fig. 1; of course, a previous detection of the odd neighbours ($i-1$ and $i+1$) of an even block i is required, so as to define $\widehat{\Delta}(i)$.

Other ways for taking advantage of the DDC algorithm are conceivable, of course. In Sec. III we propose a more sophisticated SC/FDE block transmission scheme which only requires CP assistance in the leading block of a block sequence. The performance results of sec. III also include the case where a J-branch receive diversity is employed when adopting this novel block transmission scheme.

C. DDC-FDE Performance Results

The following numerical results on SC/FDE uncoded BER performance are concerned to broadband wireless transmission over a strongly frequency-selective Rayleigh fading channel, when using the block transmission scheme of Fig. 2, with $N = 256$ data symbols per block, each one selected from a QPSK constellation (Quaternary Phase Shift Keying). We consider the power delay profile type C within HIPERLAN/2 (HIgh PERformance Local Area Network), with uncorrelated Rayleigh fading on the different paths. The duration of the useful part of the block is 5μs and the CP has duration 1.25μs, corresponding to $L = 64$ ($N/L = 4$, as in several current OFDM standards [2]).

A DDC-FDE, as shown in Fig. 1, was adopted (for ”odd” blocks, of course, $\mathbf{I}'_{\Delta L} = \mathbf{0}$ and $\tilde{\mathbf{y}}_{CP}(i) = \mathbf{y}(i) = \mathbf{y}_{CP}(i)$), and perfect synchronization and channel estimation were assumed. We point out that, for the even blocks in Fig. 2, the DDC-FDE procedures were carried out under worst-case conditions, since these blocks are CP-free.

The simulation results are depicted in Fig. 3, with dashed lines for odd blocks and solid lines for even blocks. These results show that the impact of previous decisions, which are not error-free, on the DDC-FDE receiver performance (for the even blocks) turns out to be negligible, especially for $BER < 10^{-3}$.

III. Using Channel Coding Redundancy Instead of CP Redundancy

A. Code-assisted SC/FDE Block Transmission Principles

In the following, we consider the possibility of replacing the conventional CP redundancy, not directly exploited at the receiver side (due to the removal of the corresponding guard period in the received blocks, prior to FDE processing), by a fully useful channel coding redundancy. In the transmission scheme proposed below, which takes advantage of an already available DDC algorithm, we split each length-N coded data block i into two parts: a length-$(N-L)$ ”main” block i (with

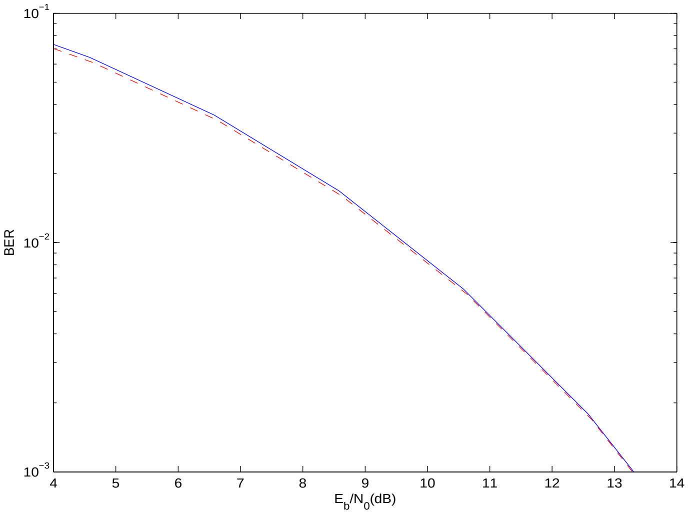

Fig. 3. Uncoded BER performance for a strongly frequency-selective Rayleigh fading channel, with $N = 256$ and $L = 64$: "odd" blocks (dashed line); "even" blocks (solid line).

$N \geq L$), including some channel coding redundancy and a length-L "complementary" block i', based on the channel coding redundancy not included in the main part.

With a sequence of M two-part coded data blocks (i, i'), the proposed frame is as shown in Fig. 4(A): it requires M contiguous, length-N, FFT windows for FDE purposes, but only requires CP assistance (full-length) in the leading block. The resulting block-transmission efficiency is $\eta = MN/(MN + L)$, which means $\eta \approx 1$ when $M >> 1$.

For the sake of comparisons, Fig. 4(B) shows the corresponding conventional scheme with the same channel coding redundancy, designed for FDE purposes on the basis of M non-contiguous, length-N, FFT windows at the receiver side, and leading to a block-transmission efficiency $\eta' = N/(N + L)$. When the gross bit rate is the same with (A) and (B) alternatives, the corresponding data rate R_b with the proposed alternative can be significantly higher than the data rate R'_b using the conventional block-transmission approach. Due to the reduced CP-overhead penalty, $R_b = R'_b M(N+L)/(MN+L)$ ($R_b \approx (1 + L/N)R'_b = R'_b/\eta'$ if $M >> 1$).

It should also be noted, as depicted in Fig. 4(C), that a conventional scheme could be aimed at providing about the same data rate R_b as the one in Fig. 4(A), at the expense of a reduced channel coding redundancy: however, a reduced coding gain, at least for similar decoding complexity, should be expected, together with the increased CP-overhead penalty.

When using the transmission scheme of Fig. 4(A), the required DDC/FDE/decoding procedures are as follows:

1. Conventional FDE for the leading block $(M', 1)$, followed by the decoding of block 1 and a subsequent re-encoding operation, so as to generate an estimate of block $1'$ (based on the extra redundancy not included in block 1).

2. [From $i = 2$ to $i = M - 1$] DDC-FDE for block $(i, (i - 1)')$, followed (possibly in parallel) by

a) Decoding of block $(i - 1, (i - 1)')$;

b) Decoding of block i, and subsequent re-encoding, so as to generate an estimate of block i'.

3. DDC-FDE for block $(M, (M - 1)')$, followed (possibly in parallel) by

a) Decoding of block $(M - 1, (M - 1)')$;

b) Decoding of block (M, M').

We point out that the decoding procedures mentioned above can be made simple, since a soft output is not required for the subsequent DDC-FDE operations (but a soft input can be recommendable, for decoding performance reasons).

In Sec. II, it was reported that, under CP-free conditions, a poor estimate of "symbol differences" for DDC-FDE purposes typically leads to an increased degradation of the last L equalized samples. In the context of the proposed code-assisted block transmission scheme, this means that the length-L blocks $1', 2', \ldots, (M - 1)'$at the DDC-FDE output typically suffer from worse quality than the equalized blocks M' and $1, 2, \ldots, M$. Therefore, the subsequent decoding for the $M - 1$ pairs $(1, 1'), (2, 2'), \ldots, (M - 1, (M - 1)')$ may not be able to exhibit the same high performance as the (M, M') decoding, which takes advantage of an equalized block M' provided by conventional FDE (not affected by error propagation).

A complementary set of operations, described below, can be carried out so as to solve this error propagation problem concerning the $M - 1$ pairs $(1, 1'), (2, 2'), \ldots, (M - 1, (M - 1)')$ (a length-L tail, preferably zero-padded, has to be appended to the frame of Fig. 4(A)):

4. [After steps 1, 2 and 3 described above] DDC-FDE procedures based on the $M - 1$ shifted FFT windows shown in Fig. 5, so as to get improved equalized samples regarding the "complementary redundancy" blocks $1', 2', \ldots, (M - 1)'$, followed by a new decoding of the resulting paired blocks $(1, 1'), (2, 2'), \ldots, (M - 1, (M - 1)')$ (The equalized samples, obtained previously, concerning the "main blocks" $(1, 2, \ldots, M - 1)$ are preserved for decoding procedures.).

B. A Coding Design Example and Performance Results in the Linear FDE Case

The ideas of III.A concerning the (i, i') splitting of each length-N coded data block can easily be made practical, by resorting to well-known channel coding schemes. In the design example described and evaluated below, we adopt a rate-1/2 convolutional code for generating each (i, i') coded data block: the "main" part (i) is obtained through a puncturing procedure [8]; the "complementary" part (i') is concerned to the redundancy previously removed by that procedure. Many other schemes could be devised, for example based on parallel concatenations of convolutional codes [9]. By using very long coded data blocks and by mapping every block onto several length-M channel block sequences such as that in Fig. 4(A) (each sequence assigned to a particular time slot), one could benefit from the well-known turbo code features.

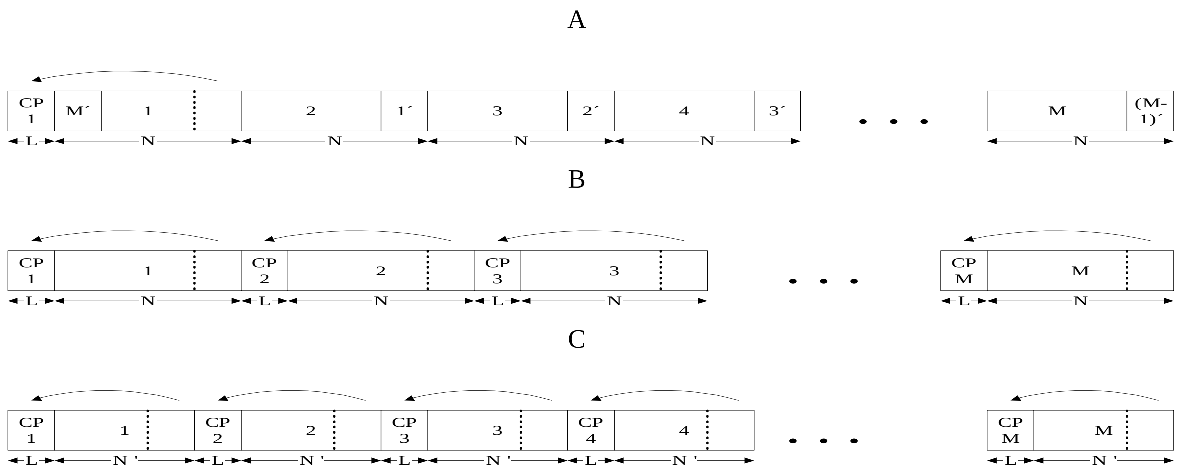

Fig. 4. Highly efficient, code-assisted block transmission scheme (A), and conventional schemes using the same channel coding redundancy (B) and, with $N' = N - L$, a reduced channel coding redundancy (C).

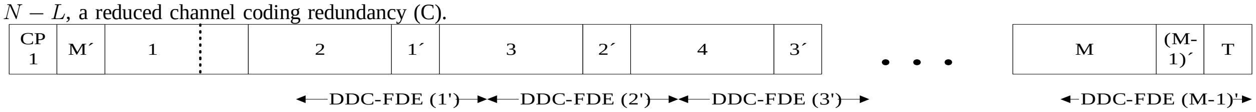

Fig. 5. Shifted length-N FFT windows for the complementary DDC-FDE procedure (T denotes the length-L required tail, preferably zero-padded).

The BER results shown below are concerned to the SC/FDE block transmission scheme of Fig. 4(A) and to the strongly frequency-selective Rayleigh fading channel already considered in Sec. II, when $L = 64$, $N = 256$, $M = 5$ and a QPSK modulation is adopted (in this case, $\eta = 20/21$). The rate-1/2 convolutional code is an optimum 64-state code, characterized by $g_1(D) = 1 + D + D^2 + D^3 + D^6$ and $g_2(D) = 1 + D^2 + D^3 + D^5 + D^6$, which is punctured to obtain a rate-2/3 code for (i, i')-splitting purposes.

We also consider the possibility of using more complex receivers, with J-branch diversity, when adopting the code-assisted block transmission approach. The required DDC-FDE (MMSE) receiver is shown in Fig. 6 (with $\hat{H}_k^{(j)}$ assumed to be employed in each DDC-j processor, $j = 1, \ldots, J$). The equalizer coefficients are as follows [3], [4]:

$$C_k = \frac{1}{\hat{\alpha} + \sum_{j=1}^{J} |\hat{H}_k^{(j)}|^2}, \tag{9}$$

with α as defined in Sec. II (the same noise level is assumed in all receiver branches).

A set of BER results is plotted in Fig. 7. They show that the error propagation effects which are inherent to the DDC algorithm become negligible, especially for the diversity case, when the complementary equalization/decoding operations (described in "Step 4" in Sec. III.A) are employed. Without Step 4, a small performance degradation (about 1dB) can be expected.

IV. Conclusions and Complementary Remarks

In this paper, devoted to SC/FDE block transmission, a low-complexity signal processing algorithm was proposed to deal with situations where the CP length is not long enough to cover the time-dispersive channel effects. This "DDC algorithm" (Decision-Directed Correction) was shown to provide good FDE performances, since the error propagation impact is negligible, even in worst-case (CP-free) conditions.

Moreover, a novel class of reduced-CP schemes was proposed in this paper, which takes advantage of the DDC algorithm for replacing "useless" CP redundancy by fully useful channel coding redundancy. A highly efficient block transmission was then shown to be achievable, through the code-assisted block transmission scheme of Fig. 4(A), which is especially recommendable for jointly quite time-dispersive and time-varying channel conditions. In fact, this is an appropriate proposal for facing the designer's dilemma with regards to 'CP overhead' and 'channel variation over the FFT block'.

Further work on synchronization and channel estimation issues, concerning schemes according to Fig. 4(A), is still required. It seems that adaptive schemes capable of tracking fast channel variations should be based on an explicit channel estimation (for both DDC and FDE purposes), differently from the approach adopted in [10]. Certainly, each channel block sequence according to Fig. 4(A) should be transmitted after a few training blocks, and the channel estimators of the receiver should be switched to a decision-directed mode (based on symbol estimates) after having processed those blocks. Anyway, with regards to fast time-varying channels, the transmission scheme of Fig. 4(A) has an obvious advantage over conventional block transmission schemes (4(B) and 4(C)): it allows high power/bandwidth efficiency ($\eta \approx 1$) while keeping N/L low enough to ensure quasi-invariant channel conditions during each "FFT block".

Other topics of interest for further research include the combination of the DDC algorithm with improved FDE schemes, possibly nonlinear (e.g., iterative block-DFE [11] or turbo equalization [12] schemes), including joint equalization/decoding issues. Namely having in mind applications

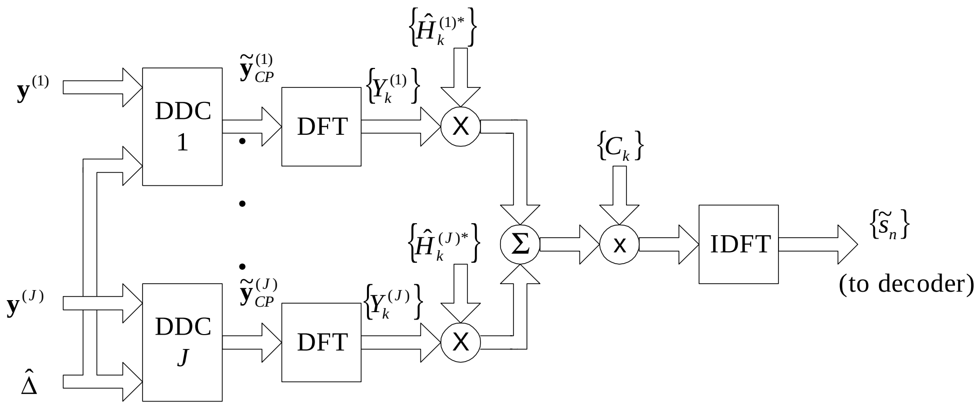

Fig. 6. DDC-FDE receiver with J-branch space diversity.

to B3G (Beyond 3rd Generation) cellular systems, a special attention should be devoted to possible adaptations of the code-assisted block transmission approach proposed here. This includes SC choices using nonlinear modulations with quasi-constant envelope and allowing good power-bandwidth trade-offs and low-complexity implementations [13], [14].

The proposed approach seems to be especially interesting for broadband wireless systems designed to operate at very high frequencies (namely in the millimeter-wave band), with full mobility and significant transmission range. The reasons are clear, having in mind those high frequencies: full mobility means strong Doppler effects, and, therefore, very fast time-varying channel conditions; a significant transmission range requires the use of amplifiers with high power efficiency (e.g., grossly nonlinear), hardly compatible with OFDM modulation schemes, since the intended mobility precludes the use of high-gain antennas with low complexity for improving the power budgets.

To conclude, it should be pointed out that the DDC-FDE algorithm can also be used to improve performances in conventional, CP-assisted, SC/FDE systems [15].

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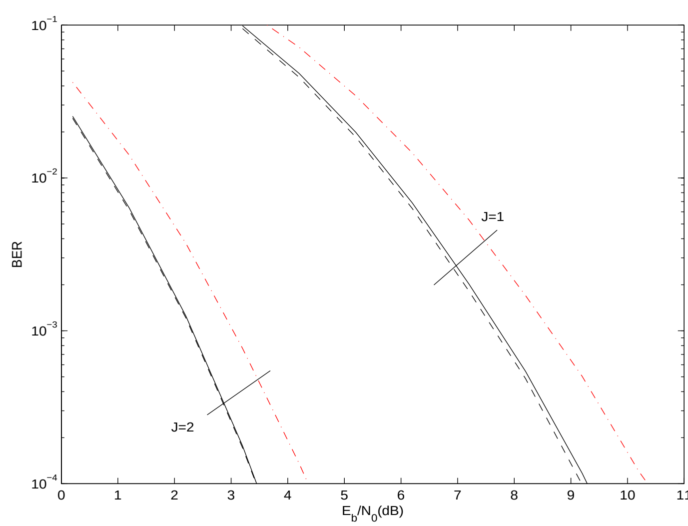

Fig. 7. BER results concerning the block transmission scheme of Fig. 4(A): under the error propagation which is inherent to the DDC procedure when the complementary equalization/decoding "Step 4" is employed (solid lines) or not (dash-dotted lines); when the simulation assumes an error-free DDC operation (dashed lines).