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MULTIPLE-INPUT HYBRID FREQUENCY-TIME DOMAIN DFE OVER TIME-VARYING RAYLEIGH-FADING CHANNEL

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ABSTRACT

In this paper, a multiple-input hybrid frequency-time domain decision feedback equalizer is proposed to deal with the intersymbol interference in time-varying frequency-selective channels. To track the time-variation in the channel, block-based adaptive processing is considered where the equalizer taps are iteratively updated with a decision directed mode. In addition, we apply the overlap-and-save technique at the receiver. This technique makes it possible to remove the overhead due to the transmission of cyclic-prefix over each block of data, such as in usual frequency-domain equalization systems. The use of multiple-input at the receiver improves the tracking of fast time-varying channels. The proposed structure is simulated over fast time-varying and frequency-selective Rayleigh-fading channel models.

1. INTRODUCTION

In high frequency-selective channels, equalization techniques are necessary at the receiver side to combat the intersymbol interference (ISI) caused by the multipath signal propagation. Among others, the decision feedback equalizers (DFE) offer better performance than linear equalizers (LE) by taking into account the interference caused by past decisions [1]. However, the DFE has the inconvenient of error propagation due to the feedback of erroneous decisions in the loop, which mainly occurs at low signal to noise ratios (SNR). Multiple antennas at the receiver side allow to improve the equivalent SNR at the equalizer output.

Frequency-domain equalization (FDE) is an interesting alternative to time-domain equalization (TDE). Based on block-processing and compared to the TDE, the gain is twofold: reduce the computational complexity at the receiver and simplify the equalizer parameters setting. This complexity reduction is increasingly important as the channel delay spread is large in terms of symbol duration. The FDE can be carried out based either on the insertion of cyclic-prefix intervals to perform a circular convolution [2, 3] or on the use of overlapping techniques to perform a linear convolution [4, 5, 6]. For spectral efficiency improvement, we use the overlapping techniques in this paper, such as the overlap-and-save (OS), which allows modifying the processed block size at the receiver unlike the

cyclic prefix based equalization.

The implementation of the DFE on a block-by-block basis is confronted to a causality problem: to compute the equalizer output corresponding to a given symbol of the current block, decisions on other symbols of the same current block are required but are not yet available. As a consequence, only the feedforward filter can be implemented on a block-by-block basis whereas the feedback filter must be implemented on a symbol-by-symbol basis. Thus, block-based FDE is applied only on the feedforward filter part. In the state of the art, this is called a hybrid frequency-time domain DFE [3, 2, 7].

In the other hand, a whole implementation of the two filters on a block-by-block basis is necessary based on iterative processing [8, 9]. Thus, A full block-based frequency-domain implementation can be carried out [3, 10]. The performance is improved with iterations, which requires higher complexity than the conventional DFE. We do not consider these iterative solutions in this paper.

Traditionally, the equalizers are designed using the minimum mean square error criterion (MMSE) based on channel estimation [11, 12] or adaptive processing [13]. When the channel impulse response (CIR) changes within block duration, that is the case in long transmissions and time-varying channels, adaptive processing enables the equalizer to track the time-variation in the channel. The equalizer taps are iteratively updated with a decision directed mode. The advantage compared to channel estimation-based equalization is that the transmission of preambles to re-estimate the channel whenever it varies is avoided. The equalizer operates with a data aided mode at the beginning of the transmission where a training sequence is sent to allow equalizer convergence to the optimal response.

When fast time-variation occurs in the channel, adaptive algorithm can not track the channel and the equalization fails. The use of multiple-inputs at the receiver offers frequency diversity and a substantial performance gain can be obtained over its single-input counterpart [14, 15]. In addition, this diversity combining gain improves the equivalent SNR at the equalizer output that reduces the error propagation phenomenon, occurring at low SNR.

In this paper, assuming no channel state information (CSI) at the receiver side and using the OS technique, we propose a multiple-input hybrid frequency-time domain adap-

tive DFE (HD-OS-ADFE) where a common feedback filter is used for all the inputs. The proposed scheme is simulated over time-varying Rayleigh-fading channel model. Results are given in terms of bit error rate (BER) vs. single to noise ratio (SNR).

2. RECEIVER DESIGN

We consider an adaptive DFE for an all-digital single-carrier receiver in a fast time-varying channel environment. The DFE is implemented on a hybrid frequency-time domain block basis. The information data are mapped onto a QPSK modulator. Each set of $m = \log_2(M)$ data is associated with an M -ary complex symbol d_n by a Gray mapping. The resulting data stream is transmitted through a multipath channel. Let $s(t)$ be the transmitted signal:

$$s(t) = \Re\{ \sum_{n=-\infty}^{+\infty} d_n g(t - nT) e^{j(2\pi f_c t + \psi)} \} \quad (1)$$

where f_c is the carrier frequency, ψ is the carrier phase uncertainty, $1/T$ is the symbol rate with T the symbol duration, $\{d_n\}$ are the QPSK transmitted symbols with variance σ_d^2 and $g(t)$ is a pulse-shaping filter.

After demodulation and sampling at the symbol rate, the received signal is modeled as the output of a single-input multiple-output (SIMO) discrete-time channel where each output m , ($m = 1, \dots, N_R$), is corrupted by an additive, zero-mean, white Gaussian noise (AWGN) $w_n^{(m)}$ with variance $\sigma_{w_n}^2$. Note that the noise samples at all outputs are assumed to be independent from each other. The n^{th} sample received by the m^{th} antenna can be written as follows,

$$r_n^{(m)} = \sum_{l=0}^{L-1} h_{n,l}^{(m)} d_{n-l} + w_n^{(m)} \quad (2)$$

where $h_{n,l}^{(m)}$ ($l = 1, \dots, L$) are the L coefficients of the multipath time-varying channel corresponding to the m^{th} antenna.

3. HYBRID FREQUENCY-TIME DOMAIN ADAPTIVE DFE

FDE is an interesting alternative to time-domain equalization for single carrier transmission systems. Using fast Fourier transform (FFT), the FDE is performed over a block of N samples by multiplying term by term these N samples by the N coefficients of the equalizer, as depicted in Fig. 1. The theoretical performance is equivalent to that of the TDE. FDE has a lower computational complexity than TDE when channel delay spread is high in terms of symbol duration.

A hybrid frequency-time domain overlap-and-save adaptive decision feedback equalizer (HD-OS-ADFE) is proposed in this paper. The feedforward filter is implemented in the frequency-domain on a block-by-block basis whereas

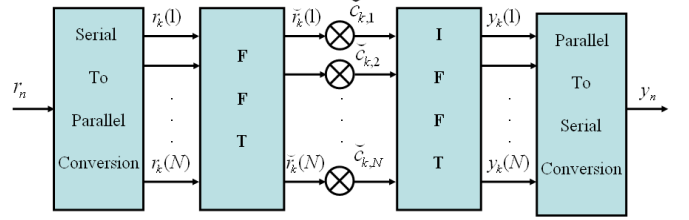


Fig. 1. Frequency-domain Equalization principle

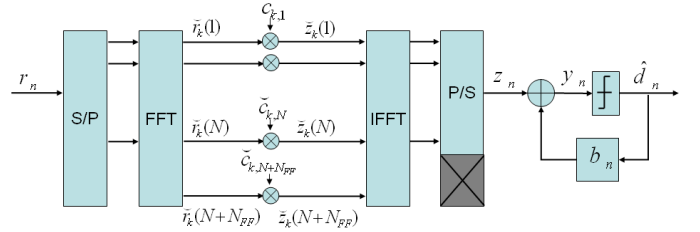


Fig. 2. Hybrid frequency-time domain DFE (HD-DFE)

the feedback filter is implemented in the time-domain on a symbol-by-symbol basis, as depicted in Fig. 2. The overlap-and-save technique is applied to the block frequency-domain feedforward part in order to avoid the overhead resulting from the transmission of cyclic prefix intervals. We denote N_{FF} the length of the feedforward filter, and N_{FB} the length of the feedback filter.

We denote \mathbf{F} and \mathbf{F}^{-1} the $(N + N_{FF}) \times (N + N_{FF})$ discrete Fourier transform (DFT) matrix and the inverse DFT matrix, respectively. The elements of \mathbf{F} are defined as follows,

$$F(s, q) = e^{-j2\pi s q / (N + N_{FF})} \quad (3)$$

After conversion to time-domain using \mathbf{F}^{-1} , the feedforward filter output block is given by the following equation,

$$\mathbf{z}_k = \text{Last } N \text{ terms of } \left\{ \mathbf{F}^{-1} \check{\mathbf{R}}_k \check{\mathbf{c}}_k \right\} \quad (4)$$

where k is the block index, $\check{\mathbf{R}}_k$ is a diagonal matrix containing the k^{th} frequency-domain overlapped input data block \mathbf{r}_k ,

$$\check{\mathbf{R}}_k = \text{diag}(\mathbf{F} \mathbf{r}_k) \quad (5)$$

\mathbf{r}_k is the time-domain overlapped input block containing the last N_{FF} elements from the previous data block and the N elements of the current data block, according to the overlap-and-save principle,

$$\mathbf{r}_k = [r_{kN-N_{FF}}, \dots, r_{kN-1}, r_{kN}, \dots, r_{kN+N-1}]^T \quad (6)$$

and finally, $\check{\mathbf{c}}_k$ is the frequency-domain feedforward filter vector containing the N_{FF} significant taps augmented by N zeros according to the overlap-and-save principle,

$$\check{\mathbf{c}}_k = \mathbf{F} [c_k, 0, \dots, 0]^T \quad (7)$$

\mathbf{c}_k is the k^{th} time-domain coefficient vector of the feedforward filter,

$$\mathbf{c}_k = [c_{k,1}, \dots, c_{k,l}, \dots, c_{k,N_{FF}}] \quad (8)$$

After parallel-to-serial conversion, data symbols are detected and filtered symbol-by-symbol by the feedback filter in the time-domain to remove the residual a-priori interference part, as given in (9).

$$y_n = z_n - \sum_{l=1}^{N_{FB}} b_{k,l} \hat{d}_{n-l} \quad (9)$$

where $b_{k,l}$ is the l^{th} component of the k^{th} time-domain feedback filter coefficient vector

$$\mathbf{b}_k = [b_{k,1}, \dots, b_{k,l}, \dots, b_{k,N_{FB}}] \quad (10)$$

Using the minimum mean square error (MMSE) criterion, the feedforward and feedback filters taps are designed based on the least mean square (LMS) adaptive algorithm, where the equalizers taps are iteratively updated. This enables to track the time-variation in the channel in a decision directed mode. However, a training sequence must be sent at the beginning of the transmission to allow the equalizer to converge to the optimal solution.

Each symbol error is evaluated as a difference between the equalizer output and the corresponding decision as follows,

$$e_n = y_n - \hat{d}(y_n) \quad (11)$$

where $\hat{d}(y_n)$ is the decision taken from y_n . The block error vector is defined as,

$$\mathbf{e}_k = [e_{kN}, e_{kN+1}, \dots, e_{kN+N-1}]^T \quad (12)$$

and the corresponding frequency-domain error block $\check{\mathbf{e}}_k$ is given as follows,

$$\check{\mathbf{e}}_k = \mathbf{F} \mathbf{e}_k \quad (13)$$

Both feedforward and feedback filters are updated on a block-by-block basis according to the hypothesis of slow time-varying channel within the block duration. In other words, the filters taps are kept fixed during the block interval and are updated at the next block iteration. The update equations are given as follows,

$$\check{\mathbf{c}}_{k+1} = \check{\mathbf{c}}_k - \mu_c \mathbf{F} \mathbf{G} \mathbf{F}^{-1} \check{\mathbf{R}}_k^H \check{\mathbf{e}}_k \quad (14)$$

for the feedforward filter, where \mathbf{G} is an $(N + N_{FF}) \times (N + N_{FF})$ time-domain constraint matrix also allowing, according to the overlap-and-save principle, to discard and insert elements when performing FFT operations,

$$\mathbf{G} = \begin{pmatrix} \mathbf{I}_{N_{FF}} & \mathbf{0}_N \\ \mathbf{0}_N & \mathbf{0}_{N_{FF}} \end{pmatrix}, \quad (15)$$

and

$$\mathbf{b}_{k+1} = \mathbf{b}_k + \mu_b \mathbf{D}_k^H \mathbf{e}_k \quad (16)$$

for the feedback filter. μ_c and μ_b are the adaptation step sizes of the feedforward filter and the feedback filter, respectively.

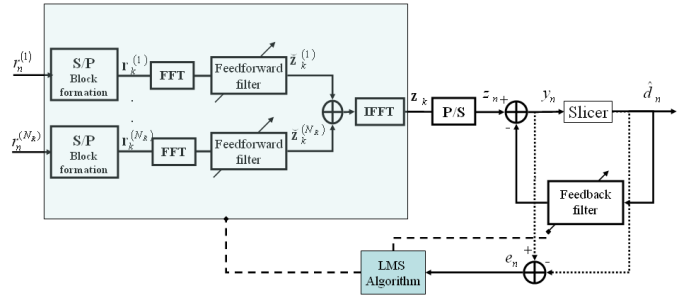


Fig. 3. Multiple-input hybrid frequency-time domain adaptive DFE

4. MULTIPLE-INPUT HD-OS-ADFE

A multiple input HD-OS-ADFE is proposed using N_R receive antennas. A common time-domain feedback filter is applied for all the inputs as depicted in Fig. 3.

The update equation of each feedforward filter vector taps for the m^{th} input is given as follows,

$$\check{\mathbf{c}}_{k+1}^{(m)} = \check{\mathbf{c}}_k^{(m)} - \mu_c^{(m)} \mathbf{F} \mathbf{G} \mathbf{F}^{-1} \check{\mathbf{R}}_k^{H(m)} \check{\mathbf{e}}_k \quad (17)$$

$\mu_c^{(m)}$ is the adaptation step-size parameter for the m^{th} input.

In each feedforward filter, an element-wise multiplication between the input data block and the filter taps is carried out. The N_R resulting blocks at the feedforward filters outputs are combined in the frequency-domain and the resulting block is returned in the time domain as follows,

$$\check{\mathbf{z}}_k^{(m)} = \check{\mathbf{R}}_k^{(m)} \check{\mathbf{c}}_k^{(m)} \quad (18)$$

$$\mathbf{z}_k = \text{Last } N \text{ terms of } \left\{ \mathbf{F}^{-1} \sum_{m=1}^{N_R} \check{\mathbf{z}}_k^{(m)} \right\} \quad (19)$$

A feedback filter is then applied as defined in section III. The multiple-input structure is simulated over time-varying Rayleigh-fading channel model. Results are presented in section V.

5. SIMULATION RESULTS

In highly frequency-selective and time-varying wireless channels, the transmitted signal experiences significant power fluctuations due to the fading caused by the multipath propagation and Doppler effect. One such well known channel model is the Rayleigh fading. Simulation over this model is of great interest in wireless communications. To generate this fading process, we use the statistical Jakes model in which the theoretical Doppler spectrum of the Rayleigh fading channel can be approximated accurately as a sum of randomly generated sinusoids [16]. Continuous data transmission is carried out over a continuous fast time-varying channel.

Table 1. Table of transmission parameters

Carrier-frequency	$f_c = 2$ GHz
Modulation	QPSK
Bandwidth	$Bw = 10$ MHz
Relative speed between the transmitter and the receiver in the case of Fig. 4	$v = 3$ km/h
Maximum frequency Doppler for Fig. 4	$f_{d_{max}} = 5.55$ Hz
Relative speed between the transmitter and the receiver in the case of Fig. 5	$v = 30$ km/h
Maximum frequency Doppler for Fig. 5	$f_{d_{max}} = 55.55$ Hz
Block length	64
Feedforward filter length	64
Feedback filter length	2
Training sequence	400 blocks

The performance are given in terms of bit error rate (BER) as a function of the signal to noise ratio E_b/N_0 , where E_b is the average energy per data bit and N_0 is the one-sided noise power spectral density. The HD-OS-ADFE is simulated over the Rayleigh-EQ3 time-varying channel model that contains three paths with equal average power. We include the theoretical matched filter bound (MFB) of Rayleigh-E3 channel model. We also include the theoretical binary error probability for an additive white Gaussian noise (AWGN) channel as a reference. The transmission simulations parameters are given in table 1. The time-variation is generated by Doppler effect and is characterized by the product of the Doppler band $B_d = 2f_{d_{max}}$ by the symbol duration T .

In Fig. 4, we show the performance of the HD-OS-ADFE in slow-time-varying Rayleigh-fading channel model with $B_dT = 0.7 \cdot 10^{-4}$. We also compare the performance of the HD-OS-ADFE to a block-based frequency-domain overlap-and-save adaptive linear equalizer (FD-OS-ALE), which contains only a feedforward filter optimized adaptively on a block-by-block basis, in the frequency-domain, as given in equation (14). The two equalizers can not track the channel variation below an E_b/N_0 value of about 6 dB in a decision directed mode. Both equalizers require a minimum E_b/N_0 value to achieve the decrease of the BER as a function of E_b/N_0 . This value is equal to 6 dB in the case of the FD-OS-ALE while it is equal to 7 dB in the case of the HD-OS-ADFE, due to the error propagation phenomenon that occurs at low SNR values. Beyond 7 dB, the HD-OS-ADFE outperforms the FD-OS-ALE and performs around 2 dB close to the lower theoretical MFB of the Rayleigh-EQ3 channel model. The FD-OS-ALE needs an E_b/N_0 equal to 10.5 dB to achieve a BER of about 10^{-2} with a gap of 2 dB compared to the HD-OS-ADFE. This difference increases with the SNR.

In Fig. 5, we consider multiple antennas at the receiver and assume a Rayleigh-EQ3 channel for each transmit-

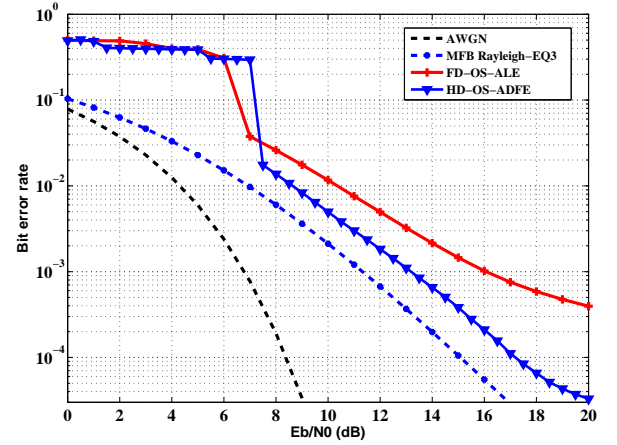


Fig. 4. Bit error rate vs. E_b/N_0 in Rayleigh-EQ3 channel model using one receive antenna, number of transmitted blocks: $1.8 \cdot 10^5$, training period: 400 blocks, $B_dT = 0.7 \cdot 10^{-4}$

antenna receive-antenna pair. We include the theoretical MFB of the Rayleigh-EQ6 channel model (i.e. 6 paths of equal average powers) using 2 inputs and the theoretical MFB of the Rayleigh-EQ9 channel model (i.e. 9 paths of equal average powers) using 3 inputs as references for the 2-input HD-OS-ADFE and the 3-input HD-OS-ADFE, respectively. We consider $B_dT = 0.7 \cdot 10^{-3}$, which yields a faster time-variation compared to Fig. 4. Consequently, the single-input HD-OS-ADFE can not track the channel and the equalization fails. When using additional receive antennas, the proposed equalizer, based on adaptive processing, is able to track the time-variation in the channel. The performance is improved as the number of receive antennas increases.

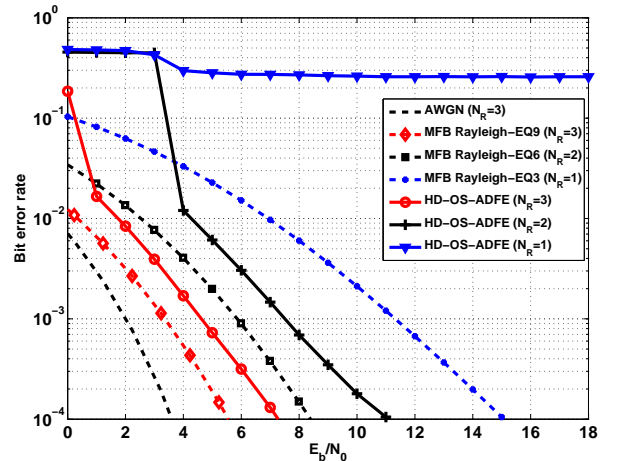


Fig. 5. Bit error rate vs. E_b/N_0 in Rayleigh-EQ3 channel model using multiple receive antennas, number of transmitted blocks: $4.2 \cdot 10^4$, training period: 400 blocks, $B_dT = 0.7 \cdot 10^{-3}$

6. CONCLUSION

In this paper, a multiple-input hybrid frequency-time domain DFE is proposed to deal with the ISI in time-varying frequency-selective channels. A block-based adaptive processing is used to track the time-variation in the channel. The frequency-domain implementation of the feedforward filter on a block basis reduces the computational complexity of the receiver compared to the time-domain DFE. When the time-variation increases in the channel, adaptive processing can not track the channel and the equalization fails. As shown through simulations, the increase in the number of receive antenna improves the performance and allows the adaptive proposed equalizer to efficiently track relatively-fast time-variations in the channel.

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