OFDM Code-Division Multiplexing with Pre-Equalization for Mobile Communications

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***Abstract*— In this paper, the potential of orthogonal frequency-division multiplexing-code-division multiplexing (OFDM-CDM) combined with the pre-equalization is investigated. The code-division multiplexing (CDM) component within an orthogonal frequency-division multiplexing (OFDM) system enables additional diversity in frequency- and time-selective mobile radio channels. While, by applying pre-equalization at the OFDM-CDM transmitter the task of equalization at the receiver can be completely avoided. Different pre-equalization techniques are investigated, and it is shown that pre-equalized OFDM-CDM systems can achieve promising performance in fading channels.**

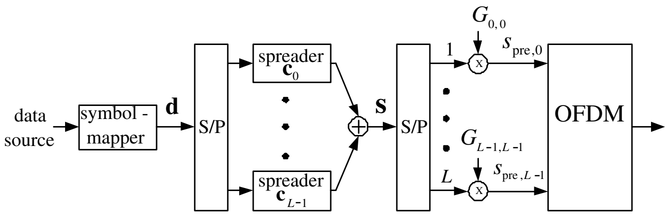

Fig. 1. OFDM-CDM transmitter with pre-equalization.

I. Introduction

In this paper, novel concept of orthogonal frequency-division multiplexing-code-division multiplexing (OFDM-CDM) [1] [2] combined with the pre-equalization at the transmitter is introduced. The CDM component within an OFDM system enables additional diversity in frequency- and time-selective mobile radio channels. The pre-equalization of multi-carrier code-division multiple-access (MC-CDMA) systems has been recently investigated by several authors [3] [4], but similar investigations for OFDM-CDM systems are still missing.

The pre-equalization operates on the premise that the channel state information (CSI) is available at the transmitter. When the CSI is known at the transmitter, pre-equalization can be applied to the transmission signal, so that the signal at the receiver appears to be non-distorted, and no additional post-equalization at the receiver is needed. For example, the CSI can be made available by using time division duplex (TDD) mode. Under the presumption that subsequent up- and down-link TDD slots are short enough compared to the coherence time of the considered fading channel, the CSI estimated from received slot can be used for pre-equalization of transmission slot.

The aim of this paper is to carry out a performance comparison of different OFDM-CDM channel pre-equalization techniques. Considered pre-equalization techniques are maximum ratio combining (MRC), equal gain combining (EGC), zero forcing (ZF) pre-equalization, controlled pre-equalization (CE), minimum mean-square error pre-equalization (MMSE), and suboptimal MMSE pre-equalization. Furthermore, the power constraint condition, that maintains the transmitted power the same as in the case without pre-equalization, is introduced. The different pre-equalization techniques with power constraint are analyzed in fading channels.

II. Transmission System

The transmitter of an OFDM-CDM system is shown in Fig. 1. The vector $\mathbf{d} = (d_0, \ldots, d_{L-1})^{\mathrm{T}}$ represents the L data symbols obtained from the symbol mapper. $(.)^{\mathrm{T}}$ denotes transposition. Each of the elements of vector $\mathbf{d}$ is multiplied with different spreading code of length L. The spreading $L \times L$ matrix

$$\mathbf{C} = (\mathbf{c}_0, \ldots, \mathbf{c}_{L-1}) = \begin{pmatrix} c_{0,0} & c_{1,0} & \cdots & c_{L-1,0} \\ c_{0,1} & c_{1,1} & \cdots & c_{L-1,1} \\ \vdots & & \ddots & \vdots \\ c_{0,L-1} & c_{1,L-1} & \cdots & c_{L-1,L-1} \end{pmatrix} \tag{1}$$

consists of the different spreading codes $\mathbf{c}_l$, $l = 0, \ldots, L-1$. The multiplication of the data symbols with the spreading matrix represents CDM component of the considered system. The result of CDM process can be written as

$$\mathbf{s} = \mathbf{C}\mathbf{d} = (s_0, \ldots, s_{L-1})^{\mathrm{T}}. \tag{2}$$

After that, pre-equalization is performed. The resulting pre-equalized vector is

$$\mathbf{s}_{\text{pre}} = \mathbf{G}\mathbf{s} = (s_{\text{pre},0}, \ldots, s_{\text{pre},L-1})^{\mathrm{T}}. \tag{3}$$

The elements of diagonal pre-equalization matrix $\mathbf{G}$ are given with $G_{l,l}, l = 0, \ldots, L-1$. They are calculated from the CSI. As already mentioned, in TDD mode the CSI can be derived from previously received slot.

The pre-equalized vector $\mathbf{s}_{\text{pre}}$ is modulated onto L sub-carriers using the OFDM. OFDM is realized by an inverse fast Fourier transform (IFFT) and a guard interval, that exceeds the delay spread of the multipath channel, is added as cyclic prefix. This finishes the process of generation of an OFDM-CDM symbol. Finally, several subsequent OFDM-CDM symbols are grouped into one OFDM-CDM frame.

Due to the frequency-selective fading of the time-variant multipath channel, and the additive white Gaussian noise (AWGN) influence, the received signal after inverse OFDM (IOFDM) can be represented as

$$\mathbf{r} = \mathbf{H}\mathbf{s}_{\mathrm{pre}} + \mathbf{n}, \tag{4}$$

where diagonal matrix $\mathbf{H}$ represents the influence of fading channel on the L subcarriers. The diagonal matrix $\mathbf{H}$ is given with its elements $H_{l,l}, l = 0, \ldots, L-1$. The vector $\mathbf{n} = (n_0, \ldots, n_{L-1})^{\mathrm{T}}$ represents the AWGN with variance σ^2.

Finally, at the receiver, the received data vector is despread and decoded.

Note, the receiver does not perform channel estimation and data equalization, since the pre-equalization is already performed at the transmitter. Thus, the receiver has very simple structure, which is very important especially in the downlink case where the simplest possible structure of the mobile station is desired.

III. Pre-equalization Techniques

The pre-equalization techniques considered in this paper are: MRC, EGC, ZF, CE, MMSE and suboptimal MMSE pre-equalization. Focus of this paper is on constrained pre-equalization, where the transmit power is the same as in the case without pre-equalization. Approaches that do not include power constraint lead to uncontrolled emission of power at the transmitter, and therefore cannot be realized in practice.

The condition for constrained pre-equalization can be derived from

$$\sum_{l=0}^{L-1} |G_{l,l} s_l|^2 = \sum_{l=0}^{L-1} |s_l|^2. \tag{5}$$

If it is presumed that each data symbol $|d_l|^2, l = 0, \ldots, L-1$, has the same transmission power, (5) reduces to

$$\sum_{l=0}^{L-1} |G_{l,l}|^2 = \sum_{l=0}^{L-1} |F_{l,l} W|^2 = L, \tag{6}$$

where $F_{l,l}$ is the equalization coefficient without power constraint and W is a normalization factor, that keeps the transmitted power constant. From (6), the normalizing factor W results in

$$W = \left(\frac{L}{\sum_{l=0}^{L-1} |F_{l,l}|^2} \right)^{\frac{1}{2}}. \tag{7}$$

Different pre-equalization techniques lead to different normalization factors W and pre-equalization coefficients $G_{l,l}$.

Maximum ratio combining pre-equalization (MRC) weights the transmitted signal with its normalized conjugate complex channel coefficient, giving

$$G_{l,l} = H_{l,l}^{*} \left(\frac{L}{\sum_{t=0}^{L-1} |H_{t,t}|^2} \right)^{\frac{1}{2}}, \tag{8}$$

where $(.)^{*}$ denotes complex conjugation.

Equal gain combining pre-equalization (EGC), also known as phase equalization, corrects only the phase shift. This results in a normalization factor $W = 1$. The assigned pre-equalization coefficient is

$$G_{l,l} = \frac{H_{l,l}^{*}}{|H_{l,l}|}. \tag{9}$$

Zero-forcing pre-equalization (ZF) restores the orthogonality between symbols and eliminates intersymbol interference (ISI) by inverting the channel fading coefficients. However, due to the power constraint condition residual fading remains which is equal for all subcarriers. Since large amounts of power are invested to pre-equalize the signal on subcarriers in deep fade, the received power on the subcarriers is very low compared to the noise level and, thus, the received signal is largely affected by AWGN. The assigned pre-equalization coefficient is

$$G_{l,l} = \frac{1}{H_{l,l}} \left(\frac{L}{\sum_{t=0}^{L-1} \frac{1}{|H_{t,t}|^2}} \right)^{\frac{1}{2}}. \tag{10}$$

Controlled pre-equalization (CE) combines EGC and ZF [5]. When the channel attenuation $|H_l|$ is below a threshold value a_{thresh} only EGC is used to prevent investing large amounts of power on weak subcarriers. Otherwise ZF is performed, this leads to

$$G_{l,l} = \begin{cases} \frac{1}{H_{l,l}} W & : \quad |H_{l,l}| \geq a_{\mathrm{thresh}} \\ \frac{H_{l,l}^{*}}{|H_{l,l}|} W & : \quad |H_{l,l}| < a_{\mathrm{thresh}}, \end{cases} \tag{11}$$

where the normalization coefficient W is equal to

$$W = \left(\frac{L}{\sum_{t=0}^{L-1} W_t} \right)^{\frac{1}{2}}, \tag{12}$$

and W_t is given by

$$W_t = \begin{cases} \frac{1}{|H_{t,t}|^2} & : \quad |H_{t,t}| \geq a_{\mathrm{thresh}} \\ 1 & : \quad |H_{t,t}| < a_{\mathrm{thresh}}. \end{cases} \tag{13}$$

Similar to the proposal in [3], an improvement can be achieved when choosing $\frac{H_{l,l}^{*}}{|H_{l,l}| a_{\mathrm{thresh}}}$ instead of $\frac{H_{l,l}^{*}}{|H_{l,l}|}$ in (11), and correspondingly $1/a_{\mathrm{thresh}}^2$ instead of 1 in (13). This solution is termed modified CE (mod-CE).

The drawback of both CE and mod-CE is that the optimum threshold value a_{thresh} must be determined by investigations carried out in advance. This optimum depends on both the current signal-to-noise ratio (SNR) and the number of multiplexed symbols.

Minimum mean-square error (MMSE) pre-equalization is the optimal pre-equalization technique for OFDM-CDM systems. MMSE pre-equalization minimizes the resulting influence of the ISI and of the AWGN. MMSE pre-equalization yields the pre-equalization coefficients

$$G_{l,l} = \frac{H_{l,l}^{*}}{\frac{L-1}{L}|H_{l,l}|^2 + \sigma^2} \left(\frac{L}{\sum_{t=0}^{L-1} \frac{|H_{t,t}|^2}{\left(\frac{L-1}{L}|H_{t,t}|^2 + \sigma^2\right)^2}} \right)^{\frac{1}{2}}. \tag{14}$$

The drawback of MMSE is that the information about the noise variance σ^2 is required at the transmitter.

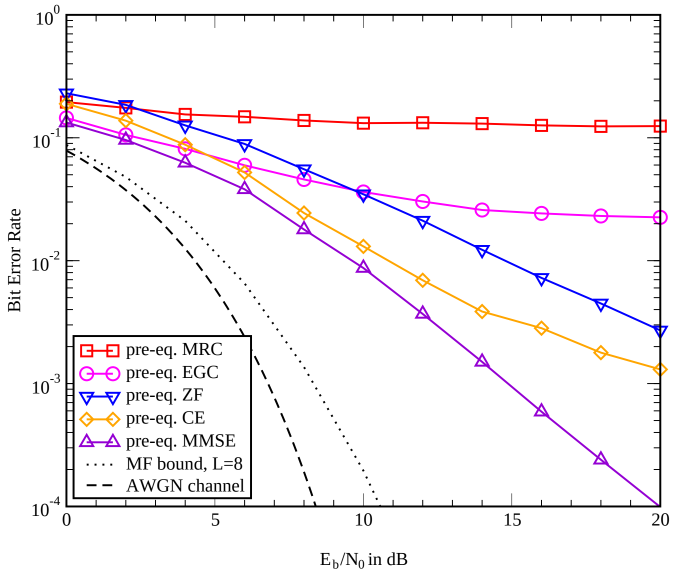

Fig. 2. Performance of basic OFDM-CDM power constrained pre-equalization techniques, spreading length L=8.

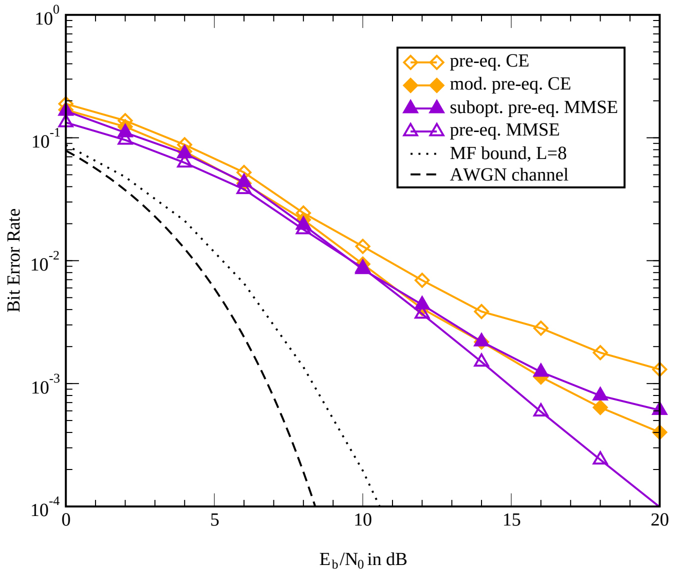

Fig. 3. Performance of CE, mod-CE, MMSE and suboptimal MMSE pre-equalization techniques, spreading length L=8.

Suboptimal MMSE pre-equalization is introduced in order to overcome the additional complexity needed for determining σ^2 at the transmitter. Suboptimal MMSE is based on similar considerations as in [3] [6]. The term σ^2 in (14) is replaced by a fixed value λ. This coefficient λ is optimized for a certain SNR value which corresponds to the maximum acceptable bit error rate for the transmission system. The assigned pre-equalization coefficient is

$$G_{l,l} = \frac{H^*_{l,l}}{\frac{L-1}{L}|H_{l,l}|^2 + \lambda} \left(\frac{L}{\sum_{t=0}^{L-1} \frac{|H_{t,t}|^2}{\left(\frac{L-1}{L}|H_{t,t}|^2 + \lambda\right)^2}} \right)^{\frac{1}{2}} . \quad (15)$$

IV. Simulation Results

In this section several simulation results that illustrate the performance of pre-equalized OFDM-CDM systems in independent Rayleigh fading channels are given. Throughout the simulations the QPSK symbol mapping is applied, Walsh-Hadamard codes are used for spreading, while spreading length and the number of subcarriers are set to $L = 8$.

Different power constrained channel pre-equalization techniques for OFDM-CDM system are compared in Fig. 2. The comparison is given in the terms of the bit error rate (BER) versus the SNR per bit. As it can be seen, MMSE pre-equalization and CE outperform other pre-equalization techniques. The performance of CE is optimized for the working point of BER $P_b = 10^{-2}$, by setting $a_{\text{thresh}} = 0.25$. For the reference the AWGN channel performance and the matched filter (MF) bound for the case $L = 8$ are given as well.

The BER versus the SNR per bit comparison of CE, mod-CE, MMSE and suboptimal MMSE is given in Fig. 3. The coefficient λ for suboptimal MMSE is optimized for the working point of BER $P_b = 10^{-2}$. The threshold value for mod-CE is set to $a_{\text{thresh}} = 0.5$ which gives the optimal performance at the working point of BER $P_b = 10^{-2}$

V. Conclusions

In this paper, the novel concept of pre-equalization within an OFDM-CDM system has been investigated. Several pre-equalization techniques have been introduced and optimal MMSE pre-equalization technique has been derived. The problem of hardware complexity required for the optimal MMSE solution has been addressed by introducing the sub-optimal MMSE pre-equalization technique. The performance results have been presented for independent Rayleigh fading channel. It has been shown that promising results can be obtained when applying pre-equalization to OFDM-CDM systems.

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