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MULTI-CARRIER SPREAD SPECTRUM AND ITS RELATIONSHIP TO SINGLE-CARRIER TRANSMISSION

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Abstract— **The combination of orthogonal frequency division multiplexing (OFDM) and code division multiplexing (CDM) has found great interest during the last few years. In contrast to a conventional OFDM system the information is spread over several subcarriers using orthogonal codes which leads to a diversity gain in frequency-selective channels. In this paper it is shown that such a system is technically equivalent to a single-carrier system with guard interval if the columns of a Fourier matrix are used as spreading codes. The pros and cons of such a system compared to an OFDM-CDM system with abritrary spreading matrix are described and discussed.**

I. INTRODUCTION

In the last years, multi-carrier transmission and especially OFDM (orthogonal frequency division multiplexing) have received much attention due to its ability of transmitting high data rates even in highly time dispersive radio channels with reasonable equalization effort. These systems are characterized by parallel data transmission over a number of generally narrowband subchannels. Recently, a combination of multi-carrier transmission and code division multiplexing (CDM) was proposed to improve the performance of multi-carrier systems [1], [2]. In this case every data symbol is spread over several subcarriers prior to subcarrier modulation and despread in the receiver, which is in fact a kind of frequency diversity. The same effect can be achieved with channel coding but it was shown in [3] that at least at code rates above 1/2 the combination of spreading and coding performs better than coding only.

In the literature, Walsh-Hadamard codes are generally used as spreading codes but in principle every other orthogonal code matrix can be applied. In this paper we will focus on the special case that the Fourier matrix is used as orthogonal code matrix. Since the multi-carrier transmission signal is generated by an inverse Fourier-transform (IFFT), both operations - spreading and IFFT - cancel each other resulting in a pure single-carrier system with blockwise processing. This fact was already mentioned in [4] but without noticing that this kind of processing combines the advantages of single-carrier transmission, like constant signal envelope, simple clock and frequency synchronization, with the advantages of OFDM-CDM like high performance in frequency-selective channels. In the following sections, a brief review of OFDM-CDM is given, followed by a detailed discussion of the resultant transmission technique and its advantages.

II. PRINCIPLE OF A MULTI-CARRIER CDM SYSTEM

With OFDM-CDM the complex data symbols x_i, $i = 1, \ldots, M$, which can be elements of any arbitrary symbol set, e.g. PSK or QAM, are spread over N subcarriers using orthogonal codes. The spreading can be described analytically by a matrix operation

$$\mathbf{s} = [\mathbf{H}] \cdot \mathbf{x} \tag{1}$$

where $\mathbf{x} = (x_1, \ldots, x_M)^T$ is the vector of data symbols, $\mathbf{s} = (s_1, \ldots, s_N)^T$ is the vector of modulation symbols and $[\mathbf{H}]$ is the code matrix of dimension $N \times M$ ($M \leq N$). Apart from spreading, the transmitter is identical to a conventional OFDM transmitter, i.e. the resulting signal sequence is IFFT-processed, periodically extended (a guard interval is added) and D/A converted, see Fig. 1. In the receiver, the inverse processing is performed, see Fig. 2.

Since the orthogonality of the spreading codes is destroyed in frequency-selective radio channels, equalization has to be implemented. In the literature various kinds of equalizers are discussed [5]-[9]. To initialize equalization, the channel transfer function has to be known and therefore channel estimation has to be performed in the receiver, too.

Due to the periodic extension of the signal in the transmitter and windowing in the receiver, the channel influence can be modelled by a cyclic convolution in the time domain or, alternatively, by a multiplication at discrete points in the frequency domain. Moreover, successive symbols do not interfere if the length of the guard interval is longer than the maximal multipath

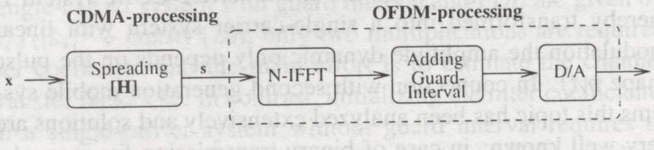

Fig. 1. Block diagram of a multi-carrier CDM transmitter

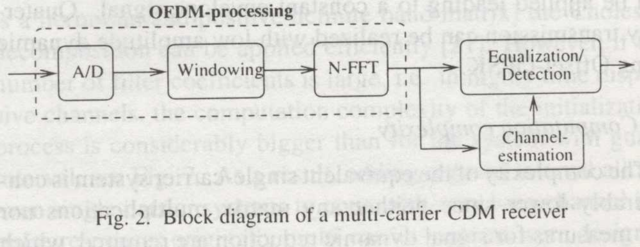

Fig. 2. Block diagram of a multi-carrier CDM receiver

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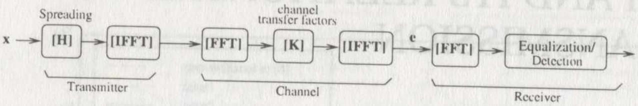

Fig. 3. Model of a multi-carrier CDM system

delay. Thus, the transmission of each symbol can be described analytically by a series of matrix multiplications as depicted in Fig. 3.

The performance of the overall transmission system does not depend on the specific type of the orthogonal spreading matrix as long as every element of the matrix has the same magnitude which means that the energy is uniformly spread over all subcarriers [10]. Considering the case that all available orthogonal codes are used, i.e. the spreading matrix is a square matrix of dimension $N \times N$, the matrix of the Fast Fourier transform meets the above mentioned demands as well as the often proposed Walsh-Hadamard matrix. If such an FFT-matrix is used spreading and OFDM processing cancel each and the transmission system degenerates into a linearly modulated single-carrier system with guard interval, i.e

$$s(t) = \sum_n x_n \cdot p(t - nT) \quad \text{where} \quad x_n = x_{n-N} \quad \text{if}$$
$$i(N + N_G) - N_G \leq n < i(N + N_G) \qquad i \in \mathbf{Z} \qquad (2)$$

In Eq. (2), the parameter N_G describes the length of the guard interval in number of data symbols spaced by the symbol duration T.

III. CONSEQUENCES FOR THE TRANSMITTER

A. Dynamic of the signal envelope

It is well known that the envelope of an OFDM signal has a high dynamic which requires a linear power amplifier in the transmitter. A lot of studies have been performed with the aim to reduce the signal dynamic of multi-carrier systems but all methods known from literature [11] - [13] have certain drawbacks. These drawbacks are either high computation complexity, large memory requirements or signal distortions. At least in the case of absolute modulation (no differential encoding) these disadvantages can be overcome if the Fourier-matrix is used for spreading. Since the multi-carrier CDM system is thereby transformed into a single-carrier system with linear modulation the amplitude dynamic only depends on the pulse shape $p(t)$. In connection with second generation mobile systems this topic has been analyzed extensively and solutions are very well known: in case of binary transmission for example, MSK (minimum shift keying), which uses a sinusoidal pulse, can be applied leading to a constant envelope signal. Quaternary transmission can be realized with low amplitude dynamic using Offset-QPSK.

B. Computation complexity

The complexity of the equivalent single-carrier system is considerably lower since neither any matrix multiplications nor any measures for signal dynamic reduction are required, which makes it very attractive for mobile applications.

IV. CONSEQUENCES FOR THE RECEIVER

A. Synchronization

To avoid interchannel interferences, an OFDM-CDM system requires a precise frequency synchronization. Generally this is achieved by the help of special synchronization symbols in combination with sophisticated frequency synchronization circuits. The equivalent single-carrier system, however, is less sensitive to frequency errors allowing simpler and therefore cheaper synchronization circuits.

B. Performance

Since the single-carrier system which results from an OFDM-CDM system with Fourier spreading matrix is a special case of an OFDM-CDM system, the same detection algorithms can be applied and the same performance can be expected.

A general block diagram of an OFDM-CDM receiver with linear equalization [8] is depicted in Fig. 4. In case of a Fourier spreading matrix, despreading in the receiver is achieved by an inverse Fast-Fourier matrix, i.e. $[\mathbf{H}]^H = [\mathbf{IFFT}]$. The overall processing corresponds to a frequency domain equalization (FDE) since the received signal vector is first Fourier-transformed, multiplied by a diagonal equalization matrix and then transformed back into the time domain. Such an FDE was originally proposed in [17] to speed up the convergence of the equalizer coefficients in conjunction with the stochastic gradient method. In [18] the FDE was picked up again to compare single-carrier and multi-carrier (OFDM) transmission but without noticing that the considered single-carrier system is a special case of an OFDM-CDM system. Recently, the FDE was discussed for use in future mobile communication systems in combination with antenna diversity [20].

In contrast to a conventional single-carrier system, the single-carrier system resulting from OFDM-CDM with Fourier spreading matrix is characterized by a guard interval and the question arises why it should be advantageous to waste some part of the bandwidth. There are two reasons: the first one is the higher performance at the same number of equalizer coefficients in case of linear or decision feedback equalization. This results from the fact that the periodic extension of the data sequence in the transmitter in connection with the signal windowing the receiver leads to a cyclic convolution of the data sequence and the discrete-time channel impulse response. If the corresponding discrete-time channel transfer function contains no zeros, this cyclic convolution can be perfectly inverted in the receiver requiring not more than N(=length of data sequence) coefficients. To achieve the same effect with a conventional single-carrier system, generally an equalizer with an infinite number of taps is required, which cannot be implemented in a real system. Thus,

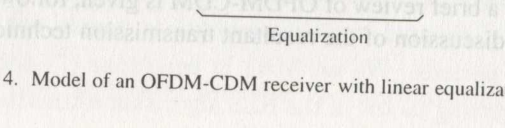

Fig. 4. Model of an OFDM-CDM receiver with linear equalization

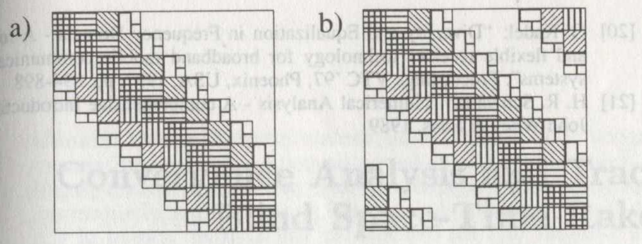

Fig. 5. Shape of the covariance matrix $[\mathbf{\Gamma}]$ in single-carrier systems a) without and b) with periodic extension (guard interval)

an equalization error occurs, which limits the performance at high signal-to-noise-ratios.

The superiority of the single-carrier system with guard-interval is proved by evaluating the minimum mean square error $J_{\min}$ at the equalizer output [19]:

$$J_{\min} = 1 - \epsilon^H [\mathbf{\Gamma}]^{-1} \epsilon \qquad (3)$$

$$[\mathbf{\Gamma}] = E\{\mathbf{e}^* \mathbf{e}^T\} \qquad \epsilon = E\{\mathbf{e}^* x\}$$

In Eq. (3) the vector $\mathbf{e}$ describes the input sequence to be filtered and x describes the desired output data, respectively. The difference between both single-carrier systems reflects in different covariance matrices $[\mathbf{\Gamma}]$ as depicted in Fig. 5. Due to the periodic extension of the data in the transmitter the covariance matrix is periodically extended as well yielding the relation

$$[\mathbf{\Gamma}](\text{with guard}) = [\mathbf{\Gamma}](\text{without guard}) + [\mathbf{\Delta}] \qquad (4)$$

with $[\mathbf{\Gamma}]$ and $[\mathbf{\Delta}]$ being hermitian matrices.

Using the relationship given in Eq. (3) and (4) it can be shown that $J_{\min}(\text{with guard}) \leq J_{\min}(\text{without guard})$.

The performance difference between a single-carrier system with and without guard interval using a stochastic channel model was additionally evaluated by Monte Carlo simulation, see Fig. 6. The applied system and channel parameters are listed below.

System parameters:
- General
  - Bandwidth $B = 2\text{MHz}$
  - linear equalization based on MMSE criterion
- OFDM-CDM with Fourier spreading matrix
  - blocklength: $T_N = 32\mu s$
  - Guardlength: $T_G = 6.6\mu s$
  - Number of symbols per block: $N = 64$
- Single-carrier system without guard interval
  - pulse with raised cosine spectral characteristic and rolloff factor $\beta = 0.2$
  - Symbol length: $T_S = 600\text{ns}$

Channel parameters:
- Exponentially decreasing power delay profile from 0 to $5\mu s$
- Rayleigh channel
- time invariant

At low signal-to-noise ratios (SNR) both systems show similar performance whereas at high SNR values an error floor can be observed if no guard interval is used. The level of the error floor depends on the type of modulation and might be of minor importance if binary or quaternary modulation is used in combination with channel coding.

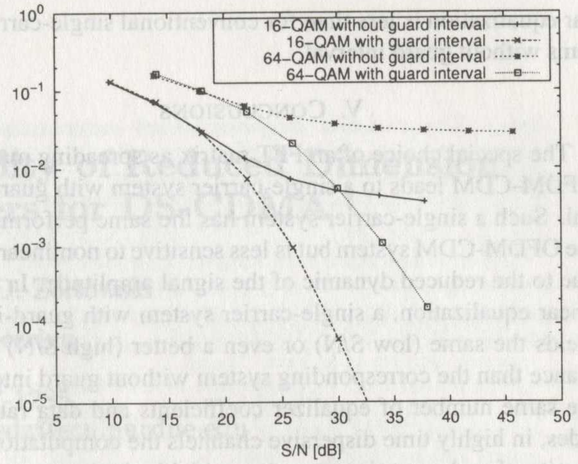

Fig. 6. Performance comparison of single-carrier systems with and without guard interval (linear equalization)

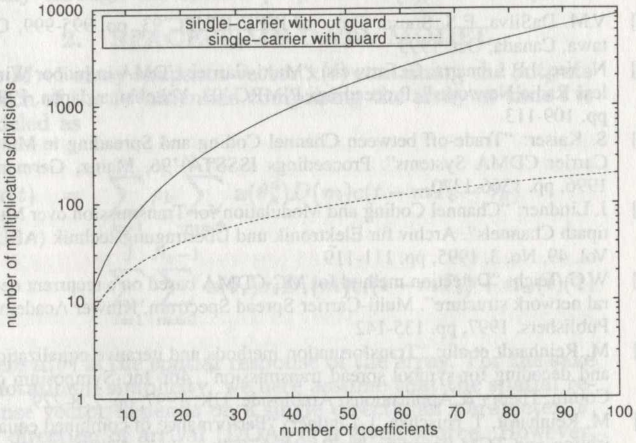

Fig. 7. Initialization effort of equalizer coefficients assuming that the channel impulse response spans 10% of the equalizer length

The second reason in favor of using a guard interval is the relatively low initialization effort of the equalizer. Since the optimum equalizer coefficients c_i, $i = 1, \ldots, N$, in case of a single-carrier system with guard interval and FDE are given by $k_i^* / (|k_i|^2 + \text{const})$ [20], only two multiplications are required per coefficient and the main effort is to estimate the channel transfer factors k_i. In contrast, initializing the filter coefficients in a single-carrier system without guard interval requires to solve the set of linear equation $[\mathbf{\Gamma}]\mathbf{c} = \epsilon$ (assuming equalization in the time domain). Due to the special form of this set ($[\mathbf{\Gamma}]$ is a hermitian and positive definite band matrix) the Cholesky decomposition can be applied efficiently [21]. However, if the number of filter coefficients is large, i.e. in highly time dispersive channels, the computation complexity of the initialization process is considerably bigger than for the system with guard interval, see Fig. 7. As a result, adding a guard interval allows even single-carrier systems to cope with very long channel impulse responses originally multi-carrier systems were designed for, since the computation complexity at least in the case of linear equalization is less than for conventional single-carrier systems without guard interval.

V. CONCLUSIONS

The special choice of an FFT matrix as spreading matrix for OFDM-CDM leads to a single-carrier system with guard interval. Such a single-carrier system has the same performance as the OFDM-CDM system but is less sensitive to nonlinear effects due to the reduced dynamic of the signal amplitude. In case of linear equalization, a single-carrier system with guard-interval yields the same (low S/N) or even a better (high S/N) performance than the corresponding system without guard interval at the same number of equalizer coefficients and data rate. Besides, in highly time dispersive channels the computation complexity of such a receiver structure with blockwise processing is considerably lower than with continuous processing.

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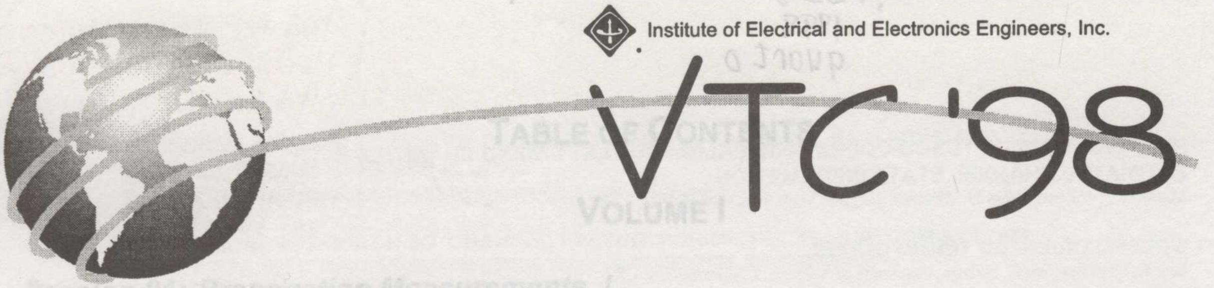

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