PERFORMANCE OF MULTI-CARRIER SPREAD-SPECTRUM SYSTEMS WITH
SPATIAL DIVERSITY AND PRE-EQUALIZATION

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ABSTRACT

In this contribution, the benefit of applying channel knowledge at the transmitter is investigated for multi-carrier spread-spectrum (MC-SS) systems. Two different MC-SS systems are observed, namely uplink multi-carrier code-division multiple-access (MC-CDMA) and spread-spectrum multi-carrier multiple-access (SS-MC-MA). The latter system is considered for both down- and uplink transmission. Pre-equalization as well as spatial diversity techniques based on transmit selection diversity and maximum ratio combining are evaluated as transmit diversity techniques which utilize channel knowledge at the transmitter. It is shown that the considered MC-SS systems can provide very promising performance with low hardware complexity.

1. INTRODUCTION

Communications systems where fading channel knowledge is exploited at the transmitter (Tx) have recently emerged as an interesting alternative to systems where fading channel knowledge is considered to be available only at the receiver (Rx). In this paper, the benefit of applying channel knowledge at Tx is investigated for two different multi-carrier spread-spectrum (MC-SS) systems, namely uplink multi-carrier code-division multiple-access (MC-CDMA) [1] [2] [3], and spread-spectrum multi-carrier multiple-access (SS-MC-MA) [4]. Whereas MC-CDMA is considered for uplink transmission only, SS-MC-MA is considered for both down- and uplink transmission. Note, SS-MC-MA systems are also known as orthogonal frequency-division multiple-access code-division multiplexing (OFDMA-CDM) systems [4].

The performance of transmission systems which are based on orthogonal frequency-division multiplexing (OFDM) can be improved by applying code-division either for multiplexing (CDM) or for multiple-access (CDMA) [4]. CDM/CDMA can be considered as a coding technique without rate loss, which can exploit time and frequency diversity in OFDM based systems. The drawback of CDM/CDMA, however, is that self-interference (SI) and multiple-access interference (MAI), respectively, might occur among the multiplexed transmission symbols. SI and MAI come from non-orthogonal spreading codes or are caused by a frequency-selective fading channel which destroys the orthogonality of the spreading codes. Note, MAI is characteristic for MC-CDMA while SI is characteristic for SS-MC-MA. One possibility to cope with MAI and SI is pre-equalization at Tx. Pre-equalization requires channel state information (CSI) at Tx. CSI can be made available at Tx for example by using time division duplex (TDD) mode. In TDD mode and under the assumption that CSI changes sufficiently slow in time [2] [5], CSI estimated from the recent received slot can be used for pre-equalization of the next transmission slot. Typically, CSI changes slowly in hot-spot and indoor scenarios, where low user mobility is assumed. By performing pre-equalization already at Tx the signal at Rx appears to be non-distorted and no additional post-equalization at Rx is necessary. Thus, Rx does not have to perform channel estimation and, therefore, can have a very simple structure which is very important especially in the downlink case.

In addition to pre-equalization, spatial diversity techniques based on transmit selection diversity (TSD) and based on transmit diversity maximum ratio combining (TD-MRC) are considered in this paper. TSD and TD-MRC require CSI only at Tx, while at Rx no channel knowledge for these schemes itself is needed. Thus, such techniques are particularly suitable for applications where CSI is available only at Tx.

The paper is organized as follows. The SS-MC-MA and uplink MC-CDMA transmission systems as investigated in this paper are described in Section 2 and 3, respectively. Simulation results are presented in Section 4. Finally, in Section 5 some conclusions are given.

2. SS-MC-MA TRANSMISSION SYSTEM

Throughout the paper, synchronous SS-MC-MA systems are considered. The obtained results of the investigations are valid for both down- and uplink transmission, since there is no conceptual difference between down- and uplink for SS-MC-MA. SS-MC-MA is an orthogonal multiple-access scheme with user discrimination in the frequency domain and, thus, without MAI. Therefore, it is sufficient to consider the transmission of a single user. For simplicity of notation, no user index is used for this single user transmission signal.

2.1 SS-MC-MA Transmitter

The block diagram of an SS-MC-MA transmitter with pre-equalization and transmit diversity is shown in Fig. 1(a). After channel coding, outer interleaving \( \Pi_{	ext{out}} \), and symbol mapping, the complex-valued symbols \( d_q \), \( q = 1, \ldots , Q \), which are to be transmitted simultaneously using CDM are multiplied, i.e., encoded by an orthogonal spreading code of length \( L \). In order to prevent a decrease in spectral efficiency due to the inner coding, \( Q = L \) encoded symbols \( d_q \) are superimposed. This results in the same symbol rate before and after spreading. It is also possible to superimpose \( Q < L \) symbols which decreases the spectral efficiency, but increases the robustness of the system [6]. Given the vector \( d = (d_1, d_2, \ldots , d_L)^T \) consisting of \( Q = L \) subsequent symbols, the inner encoding results in the encoded sequence \( s \) given by

\[
\begin{align*}
\mathbf{s} = \mathbf{C}_L \mathbf{d} = (s_1, \ldots , s_L)^T,
\end{align*}
\]

where \((\cdot)^T\) denotes transposition, and \( \mathbf{C}_L \) represents the Hadamard transformation consisting of \( L \) columns \( \mathbf{c}_k, k = 1, \ldots , L \), which represent \( L \) orthogonal spreading codes.

After the inner interleaving operation \( \Pi_{	ext{in}} \), the resulting sequence is pre-equalized and then mapped onto \( M \) data streams, where \( M \) denotes the number of Tx antennas. Each data stream is OFDM modulated onto \( N_c \) subcarriers and transmitted over its Tx antenna. The OFDM operation comprises the user-specific frequency mapper [4], inverse fast Fourier transform (IFFT), and a guard interval insertion in the form of a cyclic extension of the OFDM symbol. Depending on the size \( L_{	ext{in}} \) of the interleaver \( \Pi_{	ext{in}} \) spreading in frequency and/or time is performed [4]. Note, by choosing \( L = N_c \) several sequences can be OFDM modulated in...
parallel enabling OFDMA. For simplicity of notation but without loss of generality the interleaver $\Pi_m$ is omitted from further analysis, and it is presumed that $N_c = L$. Previous simplifications are made only for purpose of simpler notation, while simulation results are given for a simulation environment with $N_c \gg L$ which takes into account the effects of the interlaver $\Pi_m$.

2.1.1 Pre-Equalization

The sequence $s$ is pre-equalized according to

$$\bar{s} = G_{\text{pre}}s = (\bar{s}_1, \ldots, \bar{s}_L)^T,$$

where $G_{\text{pre}}$ is a diagonal $L \times L$ pre-equalization matrix with diagonal elements $G_{\text{pre},l,l}$. The elements of the pre-equalization matrix $G_{\text{pre}}$ are chosen from the diagonal $L \times L$ overall channel matrix $\hat{H}$ with diagonal elements $\hat{H}_{j,j}$, $l = 1, \ldots, L$. The overall transmission channel comprises both the applied transmit diversity scheme and the corresponding $M$ original fading channels $H_m$, $m = 1, \ldots, M$, as is explained in the following subsection. The pre-equalization elements $G_{\text{pre},j,l}$ are chosen in such a way that the power constraint is satisfied, i.e., the transmit power is the same as in the case without pre-equalization [2] [7].

The considered pre-equalization techniques are: Maximum ratio combining pre-equalization (pre-eq MRC), equal gain combining pre-equalization (pre-eq EGC), zero-forcing pre-equalization (pre-eq ZF), and minimum mean-square error pre-equalization (pre-eq MMSE). The resulting pre-equalization coefficients for the considered pre-equalization techniques are summarized in Table 1. For a more detailed discussion of pre-equalization techniques, please refer to [2] [6].

2.1.2 Transmit Diversity Mapping

The pre-equalized sequence $\bar{s}$ is mapped onto $M$ antenna-specific sequences $\bar{s}_m = (\bar{s}_{m,1}, \ldots, \bar{s}_{m,L})$ by applying the corresponding transmit diversity scheme. The mapping operation can be represented by

$$\bar{s}_{m,l} = \begin{cases} X_{m,l} s_l, & \text{for TSD} \\ \frac{H_{m,l} s_l}{\sqrt{\sum_{l'=1}^{L} |H_{m,l'}|^2}}, & \text{for TD-MRC} \end{cases}, \quad m = 1, \ldots, M,$$

where $H_{m,l}$ represents the fading coefficient on the $l$th subcarrier of the $m$th transmit antenna and $X_{m,l}$ is defined as

$$X_{m,l} = \begin{cases} 1, & \text{if } |H_{m,l}| = \max_{j=1,\ldots,M}(|H_{j,l}|) \\ 0, & \text{otherwise} \end{cases}, \quad m = 1, \ldots, M.$$

Exploiting Eq. (3) and Eq. (4) and applying several arithmetical transformations the overall transmission channel $\hat{H}$ can be obtained. Its diagonal elements $\hat{H}_{l,l}$ are equal to

$$\hat{H}_{l,l} = \begin{cases} \max_{j=1,\ldots,M}(|H_{j,l}|), & \text{for TSD} \\ \frac{\sqrt{\sum_{m=1}^{M} |H_{m,l}|^2}}{\sum_{l'=1}^{L} |H_{m,l'}|^2}, & \text{for TD-MRC}. \end{cases}$$

Note, the overall transmission channel $\hat{H}$ is used for determining the pre-equalization coefficients as indicated in Table 1.

Both considered transmit diversity techniques distribute the available transmission power over several transmit antennas with respect to CSI. It is well-known that TD-MRC is the optimal transmit diversity technique in the sense of maximization of received signal-to-noise ratio (SNR) if CSI is available at Tx [8]. The Alamouti scheme is another simple and efficient transmit diversity scheme [9]. On the contrary to TSD and TD-MRC, the Alamouti scheme requires CSI at Rx and not at Tx and, therefore, is not suitable for the MC-SS systems considered in this contribution. Moreover, since it does not maximize SNR at Rx, the Alamouti scheme leads to a lower SNR than TD-MRC and, thus, is only a suboptimum solution.

2.2 SS-MC-MA Receiver

The block diagram of an SS-MC-MA receiver is shown in Fig. 1(b). After the inverse OFDM (IOFDM) operation with user-specific frequency demapping, the received vector results in

$$r = \sum_{m=1}^{M} H_m s_m + n = (r_1, \ldots, r_L)^T,$$

where $H_m$ represents the diagonal $L \times L$ antenna-specific channel matrix with diagonal elements $H_{m,l}$. The vector $n = (n_1, \ldots, n_L)^T$ represents the AWGN with variance $\sigma^2$.

The received signal $r$ is, as shown in Fig. 1(b), deinterleaved, despread, and demapped. The symbol demapper outputs the real-valued soft decided bit $\omega$. The optimum soft decided information which can be exploited in a Viterbi decoder is the log-likelihood ratio (LLR) [10]. The LLR for pre-equalized SS-MC-MA systems can be calculated similarly to the LLR for standard SS-MC-MA systems. The standard SS-MC-MA system and its LLR calculations are given in [6]. In the case when CSI is not available at Rx, the LLR can be approximated by

$$LLR \approx \omega.$$
3. UPLINK MC-C DMA TRANSMISSION SYSTEM

In this section, a synchronous uplink MC-CDMA transmission system is considered. The analysis of pre-equalization, ZFD, and TD-MRC is completely analogous to the corresponding analysis given for SS-MC-MA and, therefore, will not be repeated in this section.

Note, the only difference is that the SS-MC-MA pre-equalization technique named pre-eq MMSE has to be slightly adapted. In the case of uplink MC-CDMA the parameter \( Q \) given in Table 1 corresponds to the number of active users \( K \). In addition, the corresponding pre-equalization coefficient for uplink MC-CDMA is only optimal in the case of a fully-loaded system and, therefore, will not be repeated in this section.

MRC is completely analogous to the corresponding analysis given in Fig. 2(a). After channel coding, outer interleaving \( \Pi_{\text{out}} \), and symbol mapping, the complex-valued symbol \( c_k \) is spread by an orthogonal spreading code \( \Phi_k \) of length \( L \). The spreading process results in the sequence \( s(k) \) given by

\[
s(k) = c_k d(k) = (s_1(k), \ldots, s_L(k))_T.
\]

(8)

After the inner interleaving operation \( \Pi_{\text{in}} \), the resulting sequence is pre-equalized and a new signal

\[
g(k) = (\tilde{s}_1(k), \ldots, \tilde{s}_L(k))_T
\]

(9)

generated. The pre-equalized signal is mapped onto \( M \) antenna-specific vectors

\[
\tilde{s}_m(k) = (\tilde{s}_{m,1}(k), \ldots, \tilde{s}_{m,L}(k))_T, \quad m = 1, \ldots, M,
\]

(10)

applying the corresponding transmit diversity scheme, i.e., TSD or TD-MRC. Each vector \( \tilde{s}_m(k) \) is OFDM modulated onto the \( N_c \) subcarriers of the corresponding Tx antenna and transmitted. OFDM comprises IFFT, and a guard interval insertion in the form of cyclic extension. As for SS-MC-MA the interleaver \( \Pi_{\text{in}} \) is omitted from further analysis, and it is presumed that \( N_c = L \) while the simulation results take into account the effects of the interleaver \( \Pi_{\text{in}} \).

3.2 Uplink MC-CDMA Receiver

The block diagram of an uplink MC-CDMA receiver is shown in Fig. 2(b). At Rx, the received signal after IOFDM operation results in

\[
r = \sum_{k=1}^{K} \sum_{m=1}^{M} H_{m,k}^{(d)} \tilde{s}_m(k) + n = (r_1, \ldots, r_L)_T
\]

(11)

where \( H_{m,k}^{(d)} \) represents the diagonal \( L \times L \) channel matrix with the diagonal elements \( H_{m,k}^{(d)} \). Each element \( H_{m,k}^{(d)} \) represents the fading coefficient on the \( k \)th subcarrier of the \( m \)th antenna of the fading channel of the \( k \)th user.

As shown in Fig. 2(b), the received IOFDM demodulated signal \( r \) is deinterleaved, despread, and demapped. The symbol demapper outputs the real-valued soft decided bit \( \omega \). The LLR approximation as given by Eq. (7) is used. Finally, the sequence of LLR values is soft decoded by applying the Viterbi algorithm and the vector of detected source bits is output from the channel decoder.

4. SIMULATION RESULTS

The performance of both SS-MC-MA and uplink MC-CDMA systems with pre-equalization and transmit diversity in Rayleigh fading channels is presented in this section. The transmission bandwidth of the considered TDD system is \( 20 \) MHz and the carrier frequency is fixed at \( 5 \) GHz. The number of subcarriers is set to 1024, producing OFDM symbols of duration 51.2 \( \mu \)s. The guard interval is chosen in such a way that it exceeds the maximal delay of the mobile radio channel. Walsh-Hadamard codes of length \( L = 8 \) are used for spreading. The depth of the interleaver \( \Pi_{\text{in}} \) and the length of the OFDM frame are equal to 24 subsequent OFDM symbols. With that spreading in time and frequency is enabled. For decoding, convolutional codes with rate \( R = 1/2 \) and memory \( m = 6 \) are applied throughout the simulations. QPSK is used for symbol mapping.

Transmit diversity is enabled using up to \( M = 2 \) transmit antennas. It is assumed that the transmit antennas are spaced apart sufficiently leading to statistically independent transmission channels from Tx to Rx. Moreover, perfect interleaving in time and frequency is assumed and, thus, independent Rayleigh fading on each subcarrier is considered. The overall transmission power is kept constant, i.e., the transmitted power per antenna decreases as the number of transmit antennas increases. Thus, a better comparison with a variable number of antennas is enabled.

Note, throughout the simulations the BER versus the SNR in \( E_b/N_0 \) is observed, where \( E_b/N_0 \) represents the transmitted energy per bit \( E_b \) over the noise spectral density \( N_0 \) at reception.

The BER versus the \( E_b/N_0 \) of an SS-MC-MA system with and without transmit diversity for pre-eq MRC and pre-eq ZF is shown in Fig. 3. Simulation results are given for 1 or 2 Tx antennas. It can be seen that pre-eq ZF with TD-MRC outperforms all other techniques. Moreover, the benefits of transmit diversity are clearly visi-
It is shown that SS-MC-MA and full-loaded uplink MC-CDMA achieve nearly the same performance. Considering pre-eq MMSE and TD-MRC with 2 Tx antennas, a BER of $10^{-5}$ is already achieved for an $E_b/N_0$ of approximately 1.5 dB for a fully-loaded system in a Rayleigh fading channel environment. Due to the simple Rx structure and the promising performance, the combination of TD-MRC with pre-equalization within an SS-MC-MA system is a very interesting, low-complex downlink candidate for future air interfaces. Considering uplink transmission both fully-loaded MC-CDMA and SS-MC-MA perform similarly. Thus, other aspects such as peak-to-average power ratio, hardware complexity, and average system load should be taken into account to make a valid preference.

REFERENCES


5. CONCLUSIONS

Two different multi-carrier spread-spectrum techniques, namely SS-MC-MA and uplink MC-CDMA, are investigated in fading channels with pre-equalization and spatial diversity at Tx. The focus of the investigations is on TDD mobile radio systems which can exploit channel knowledge at Tx. Since pre-equalization is already done at Tx, no additional equalization has to be performed at Rx and, therefore, Rx can have a very simple structure. In addition to pre-equalization, two transmit diversity techniques namely, transmit selection diversity (TSD) and transmit diversity based on maximum ratio combining (TD-MRC), which do not require any additional signal combining at Rx and, therefore, do not add complexity at Rx are considered in this contribution.