Performance Evaluation of SS-MC-MA Up-link Transmission with User Frequency Offsets

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***Abstract*: In this paper, frequency offsets among the different users within a Spread-Spectrum Multi-Carrier Multiple-Access (SS-MC-MA) system for up-link transmission over an independent Rayleigh fading channel are considered and their influence on the performance is investigated. Since SS-MC-MA can be viewed as a combination of Orthogonal Frequency-Division Multiple-Access (OFDMA) with Code-Division Multiplexing (CDM), the Inter-Carrier Interference (ICI) caused by the frequency offsets is in fact Multiple-Access Interference (MAI). We derive an analytical expression for the variance of the MAI caused by the user frequency offsets and use the Gaussian approximation to give a closed form solution for the Bit Error Rate (BER) calculation. A comparison between the theoretically obtained results and simulations prove the validity of our approach. Based on the analytical results for the MAI, we propose a novel method to combat the influence of user frequency offsets on the SS-MC-MA performance which is called block interleaving with additional spreading in time direction. As a result, this countermeasure is capable of significantly reducing the influence of frequency offsets on the performance of an SS-MC-MA up-link transmission.**

1. Introduction

SS-MC-MA [1] [2] is a promising candidate for fourth generation mobile communications, for both down-link and up-link transmission. The idea behind SS-MC-MA is to combine OFDMA with CDM. Due to the OFDMA component SS-MC-MA is an orthogonal FDMA scheme and simple pilot-aided channel estimation can be applied for the down-link as well as for the up-link. Moreover, the CDM component enables frequency diversity, because the transmitted symbols are spread in frequency before transmission. Other advantages of the OFDMA transmission scheme are retained in SS-MC-MA, like avoidance of interference between adjacent SS-MC-MA symbols by use of a guard interval or coarse time synchronization requirements. However, SS-MC-MA is very sensitive to frequency offsets among the different user signals just like OFDMA is [3].

In this paper, we investigate the influence of user frequency offsets on the performance of an SS-MC-MA up-link transmission system with Minimum Mean-Square Error (MMSE) receiver and derive an analytical expression for the variance of the resulting MAI for the case of independent Rayleigh fading. Taking into account that not only MAI but also Inter-Symbol Interference (ISI) is present and using the ISI variance as derived in [4], a closed form solution for the BER calculation is obtained by applying the Gaussian approximation. Note, ISI is due to the CDM component and is not an effect caused by frequency offsets.

Considering the analytical results for the MAI in detail, it becomes obvious that certain subcarriers contribute considerable to the MAI whereas other subcarrier contributions are negligible. Based on this fact, a novel method to combat the influence of user frequency offsets is proposed. Especially, we combine standard block interleaving with additional spreading in time direction in order to make subcarriers with considerable MAI contribution orthogonal to the information bearing subcarriers of the desired user. As a result, the MAI is decreased considerably when applying this novel method.

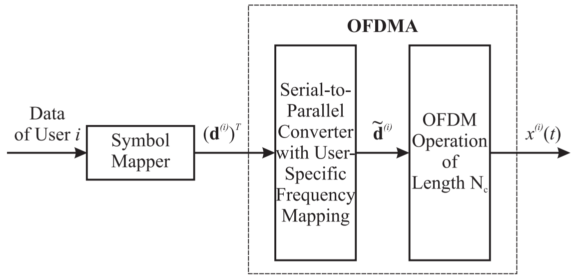

Figure 1: Block diagram of an OFDMA transmitter for up-link transmission.

This paper is organized as follows. In Section 2, we describe the SS-MC-MA system together with the standard block interleaving scheme. The analytical derivation of the MAI variance is developed in Section 3. Moreover, the analytical BER calculation based on the Gaussian approximation and taking into account both MAI and ISI is given. In Section 4, we discuss the MAI within an SS-MC-MA up-link transmission system and propose a novel method to combat the MAI. Simulation results are presented in Section 5 and Section 6 concludes this paper.

2. System Description for SS-MC-MA

Multiple-access in SS-MC-MA is done by using OFDMA. The block diagram of an OFDMA up-link transmitter is shown in Figure 1. The symbol vector $\mathbf{d}^{(i)}$ of user i, $i = 0, .., K-1$, contains Q complex-valued symbols

$$\mathbf{d}^{(i)} = (d_0^{(i)}, d_1^{(i)}, \ldots, d_{Q-1}^{(i)})^T. \qquad (1)$$

The row vector $(\mathbf{d}^{(i)})^T$ is first serial-to-parallel converted and then an user-specific frequency mapping of the Q symbols onto the $N_c = KQ$ available subcarriers is applied. This results in a new symbol vector $\tilde{\mathbf{d}}^{(i)}$ which consists of N_c components of which only Q components are non-zero. The remaining $(K-1)Q$ subcarriers enable up to $K-1$ other users to transmit Q symbols simultaneously with their own set of Q subcarriers. The

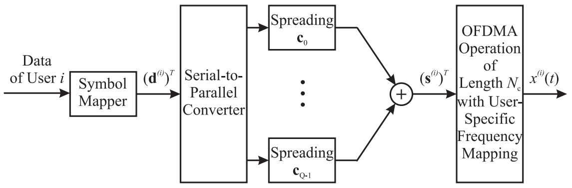

Figure 2: Block diagram of an SS-MC-MA transmitter for up-link transmission.

applied frequency allocation scheme is standard block interleaving where the symbols of user i are distributed equally over all possible subcarriers. This scheme enables frequency diversity if coded OFDMA or an additional CDM component as in SS-MC-MA is used. However, this scheme is quite sensitive to user frequency offsets.

Mathematically, block interleaving can be described as follows. Let $f_p, p = 0, \ldots, N_c - 1$, denote the different subcarrier frequencies. Then the Q symbols q, $q = 0, \ldots, Q-1$, of user i, $i = 0, \ldots, K-1$, are allocated according

$$p = q \cdot K + i, \tag{2}$$

where p denotes the index of the subcarrier frequency f_p.

The difference between OFDMA and SS-MC-MA is, that SS-MC-MA has an additional CDM component before applying OFDMA. Figure 2 shows the block diagram of an SS-MC-MA up-link transmitter. As for OFDMA, the row vector $(\mathbf{d}^{(i)})^T$ which contains the Q complex-valued symbols of user i, $i = 0, .., K-1$, is first serial-to-parallel converted. Then, however, a CDM component is introduced by spreading each symbol with a different spreading code $\mathbf{c}_q, q = 0, \ldots, Q-1$, of length L and adding together the resulting spread Q symbols. For spreading the orthogonal Walsh-Hadamard codes are used. Since the number of symbols Q is chosen to be equal to the maximum number L of available orthogonal spreading sequences, the transmission system is said to be fully-loaded. The resulting vector $\mathbf{s}^{(i)}$ after the summation can be represented by

$$\mathbf{s}^{(i)} = \mathbf{C} \cdot \mathbf{d}^{(i)}, \tag{3}$$

where $\mathbf{C}$ is the spreading matrix which has the spreading codes $\mathbf{c}_q$, as columns. Finally, OFDMA with user-specific frequency mapping is performed for the row vector $(\mathbf{s}^{(i)})^T$. Block interleaving achieves optimal frequency diversity, since it distributes the L chips of the Q symbols of user i equally over the whole transmission bandwidth. Note, SS-MC-MA exclusively assigns to each of the K users a set of L frequencies out of all possible $N_c = KL$ subcarriers [1]. As in standard OFDMA, a guard interval larger than the maximum channel delay is added as cyclic prefix in SS-MC-MA in order to avoid interference from preceding SS-MC-MA transmission symbols.

The SS-MC-MA system under consideration is composed of $N_c = 2048$ subcarriers, $L = 64$ subcarriers for each of the possible $K = 32$ users. Per SS-MC-MA symbol $Q = 64$ information symbols multiplexed by CDM are transmitted. For simplicity, we assume BPSK modulation in the following. Walsh Hadamard codes of length $L = 64$ are applied for CDM. Note, ISI among the Q symbols of one SS-MC-MA symbol occurs, if the subcarriers carrying the L chips of the Q symbols experience different channel fading coefficients. Throughout this article we assume independent Rayleigh fading for the L subcarriers of each user. This assumption is reasonable since the L subcarriers are equally distributed over the whole transmission bandwidth due to the considered block interleaving scheme. In addition, we assume perfect channel estimation and, thus, perfect knowledge of the transmission channel. At the base station receiver, MMSE is applied for equalization of the received signal from user i which is the user under investigation. Moreover, it is assumed that user i is perfectly synchronized in frequency and that all other users k, $k \neq i$, are misaligned in frequency with certain frequency offsets. All users are perfectly synchronized in time.

3. Analytical Performance Evaluation

The analytical performance evaluation is based on the frequency domain representation of the SS-MC-MA uplink transmission. The frequency representation $\mathbf{s}^{(i)}$ of the SS-MC-MA transmission signal vector of user i is described by Equation (3). The L chips of the Q BPSK symbols of user i, which are multiplexed using CDM, are transmitted on L of the $N_c = KL$ available subcarriers. The SS-MC-MA up-link transmission signal on a single subcarrier l, $l = 0, \ldots, L-1$, is given by

$$s_l^{(i)} = \sum_{q=0}^{Q-1} c_{l,q} \cdot d_q^{(i)}, \tag{4}$$

where $c_{l,q} \in \{\frac{-1}{\sqrt{L}}, \frac{1}{\sqrt{L}}\}$ is the l-th component of the spreading code $\mathbf{c}_q$, $q = 0, \ldots, Q-1$.

In the case of block interleaving, the fictitious transmission signal vector $\hat{\mathbf{s}}$ which contains all users' transmission signals is built from the transmission signal vector $\mathbf{s}^{(i)}$ according to

$$\hat{s}_{lK+i} = s_l^{(i)}, l = 0, \ldots, L-1, i = 0, \ldots, K-1. \tag{5}$$

The focus for the analytical performance evaluation is on the uplink transmission of a certain user i, $i = 0, \ldots, K-1$. Thus, instead of the fictitious transmission signal vector $\hat{\mathbf{s}}$ the transmission signal vector $\mathbf{s}^{(i)}$ and its corresponding received signal vector $\mathbf{r}^{(i)}$ are considered in the following for simplicity.

First of all, SS-MC-MA uplink transmission without frequency offsets is considered. In this case, each subcarrier l of user i is only influenced by a complex-valued channel coefficient $H_l^{(i)}$ and the received signal $r_l^{(i)}$ on subcarrier l results in

$$r_l^{(i)} = s_l^{(i)} H_l^{(i)} + \eta_l, \tag{6}$$

where η_l represents additive white Gaussian noise (AWGN) with two-sided noise power spectral density $\frac{N_0}{2}$. At the receiver MMSE equalization is performed. Each subcarrier l of user i is multiplied with the complex-valued MMSE equalizer coefficient

$$G_l^{(i)} = \frac{H_l^{(i)*}}{|H_l^{(i)}|^2 + \frac{1}{\xi}}, \tag{7}$$

where "*" denotes complex conjugation and $\xi = 2QE_b/LN_0$ defines the Signal-to-Noise Ratio (SNR) per carrier. E_b is the average bit energy and E_b/N_0 forms the overall SNR at the receiver. Applying MMSE equalization to the received signal $r_l^{(i)}$ on each subcarrier, the equalized received signal $\tilde{r}_l^{(i)}$ on subcarrier l is obtained

$$\tilde{r}_l^{(i)} = s_l^{(i)} H_l^{(i)} G_l^{(i)} + G_l^{(i)} \eta_l. \tag{8}$$

Taking into account user frequency offsets the influence from other subcarriers on the L subcarriers of the desired user i has to be considered. This changes Equation (8) to

$$\tilde{r}_l^{(i)} = s_l^{(i)} H_l^{(i)} G_l^{(i)} U_0(\varepsilon^{(i)}) + \sum_{\substack{k=0\\k\neq i}}^{K-1} \sum_{m=0}^{L-1} s_m^{(k)} H_m^{(k)} G_l^{(i)} U_{mK+k-lK-i}(\varepsilon^{(k)}) + G_l^{(i)} \eta_l, \tag{9}$$

where $\varepsilon^{(k)}$, $k = 0, \ldots, K-1$, is the normalized frequency offset of user k at the receiver which is given as the ratio between the carrier frequency offset of user k and the subcarrier spacing. The function $U_n(\varepsilon)$ evaluated for certain n and ε describes the ICI coefficient and according to [5] is given by

$$U_n(\varepsilon) = \frac{\sin \pi(n+\varepsilon)}{N_c \sin \frac{\pi}{N_c}(n+\varepsilon)} e^{j\pi(1-\frac{1}{N_c})(n+\varepsilon)}. \tag{10}$$

Since the focus of the investigation is on the influence of misaligned users on the desired user i, it is assumed that the frequency offset of the desired user i is $\varepsilon^{(i)} = 0$ and, thus, $U_0(\varepsilon^{(i)}) = 1$. In the following, two cases are under consideration in this paper. In the first case, the frequency offsets of all users are assumed to be constant and equal resulting in $\varepsilon^{(k)} = \varepsilon$ for $k = 0, \ldots, K-1$, $k \neq i$. In the second case, the angle of distribution of the received signal from user k, $k \neq i$, at the base station is assumed to be uniformly distributed, which is a kind of "worst case" assumption. Thus, different values $\varepsilon^{(k)}$ result for each user k, $k \neq i$, and these values $\varepsilon^{(k)}$ are taken from a Jakes distribution. For this case, the maximal normalized frequency offset is denoted by $\varepsilon_{\max}$.

After despreading the received and equalized signal $\tilde{r}_l^{(i)}$ of user i an estimate $y_q^{(i)}$ for each transmitted data symbol $d_q^{(i)}$, $q = 0, \ldots, Q-1$, is obtained

$$y_q^{(i)} = \underbrace{\frac{d_q^{(i)}}{L} \sum_{l=0}^{L-1} H_l^{(i)} G_l^{(i)}}_{\alpha} + \underbrace{\sum_{\substack{p=0\\p\neq q}}^{Q-1} d_p^{(i)} \sum_{l=0}^{L-1} c_{l,q} c_{l,p} H_l^{(i)} G_l^{(i)}}_{\beta} + \underbrace{\sum_{\substack{k=0\\k\neq i}}^{K-1} \sum_{p=0}^{Q-1} d_p^{(k)} \sum_{l=0}^{L-1} \sum_{m=0}^{L-1} c_{l,q} c_{m,p} H_m^{(k)} G_l^{(i)} U_{mK+k-lK-i}(\varepsilon^{(k)})}_{\gamma} + \underbrace{\sum_{l=0}^{L-1} c_{l,q} G_l^{(i)} \eta_q}_{\eta}, \tag{11}$$

where α represents the useful signal part, β the ISI, γ the MAI, and η the noise term. Based on Equation (11) the BER calculation is derived in the following. It can be assumed that ISI β, MAI γ, and the noise term η are independent random variables. Moreover, it is shown that the probability density functions of β and γ can be well approximated by a zero mean Gaussian distribution. Thus, the Gaussian approximation can be invoked for the BER calculation. In a first step, the energy E_α of the useful signal part as well as the variances σ_β^2, σ_γ^2, and σ_η of the random variables β, γ, and η have to be determined, respectively. During this process, the product $H_l^{(i)} G_l^{(i)}$ is treated as a real-valued random variables HG.

In order to calculate the energy E_α of the useful signal part, we follow the procedure as described in [4], where it is shown that for large L the energy term E_α can be approximated by a constant value

$$E_\alpha \approx |\mathbf{E}\{HG\}|^2 E_b. \tag{12}$$

In the considered case of independent Rayleigh fading and MMSE equalization, Equation (12) can be further evaluated resulting in [1]

$$E_\alpha \approx |\mathbf{E}\{HG\}|^2 E_b = \left[1 + \frac{e^{1/\xi}}{\xi} \mathrm{Ei}\left(-\frac{1}{\xi}\right)\right]^2 E_b, \tag{13}$$

where $\mathrm{Ei}(-1/\xi)$ is the exponential integral defined as

$$\mathrm{Ei}\left(-\frac{1}{\xi}\right) = -\int_{1/\xi}^{\infty} \frac{e^{-x}}{x} dx. \tag{14}$$

Note, as already previously defined ξ is the SNR per subcarrier. The variance σ_β^2 of the ISI β coincides with the expression for the variance of the MAI in MC-CDMA systems and, thus, is given by [4]

$$\sigma_\beta^2 \approx \frac{Q-1}{L}[\mathbf{E}\{|GH|^2\} - |\mathbf{E}\{GH\}|^2] E_b = \frac{Q-1}{L}\left[\frac{1}{\xi} + \frac{e^{1/\xi}}{\xi^2}\mathrm{Ei}\left(-\frac{1}{\xi}\right) - \frac{e^{2/\xi}}{\xi^2}\mathrm{Ei}^2\left(-\frac{1}{\xi}\right)\right] E_b. \tag{15}$$

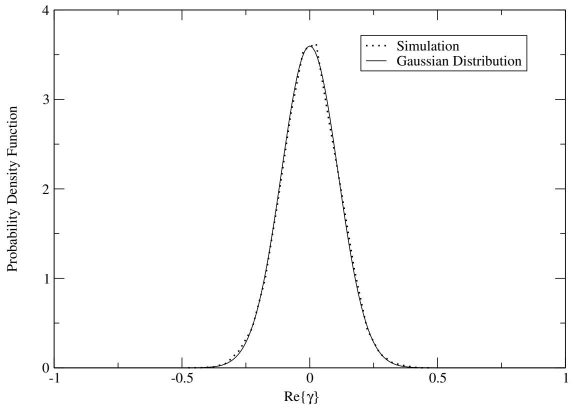

Figure 3: Simulated probability density function of $\Re\{\gamma\}$ in comparison with a fitted Gaussian distribution. Simulation parameters: $K = 32$, $L = 64$, $Q = 64$, $\varepsilon = 0.1$, and $\xi = 4$ dB

In [4], it is proven that the probability density function of the ISI β is approximately Gaussian with zero mean. The variance σ_γ^2 of the MAI γ is defined as $\sigma_\gamma^2 = \mathbf{E}\{\Re^2\{\gamma\}\}$ and results in

$$\sigma_\gamma^2 = E_b \sum_{\substack{k=0\\k\neq i}}^{K-1} \sum_{p=0}^{Q-1} \mathbf{E}\left\{\Re^2\left(\sum_{l=0}^{L-1}\sum_{m=0}^{L-1} c_{l,q} c_{m,p} H_m^{(k)} G_l^{(i)} U_{mK+k-lK-i}(\varepsilon^{(k)})\right)\right\}. \quad (16)$$

The exact analytical expression of the MAI variance σ_γ^2 is difficult to obtain. However, it is possible to use simple simulations for determing σ_γ^2, since only complex-valued Gaussian distributed random variables have to be generated for this purpose. Further investigations of Equation (16) by simulations show that the MAI variance σ_γ^2 is almost independent of the symbol index q, although Equation (16) indicates a possible dependence. That means, the MAI interference σ_γ^2 is nearly the same for all symbol indices q, $q = 0, \ldots, Q-1$. For this reason the index q is omitted in the MAI notation. To further evaluate the MAI γ the probability density function of $\Re\{\gamma\}$ is simulated for parameters $K = 32$, $L = 64$, $Q = 64$, $\varepsilon = 0.1$, and different SNR per subcarriers values ξ. The simulations show, that the MAI is approximately Gaussian distributed with zero mean. An example of simulation results for $\xi = 4$dB is shown in Figure 3.

The variance of the additive zero mean Gaussian noise η can be approximated as follows

$$\sigma_\eta^2 \approx E\{|G|^2\}\frac{N_0}{2}. \quad (17)$$

This expression can be further evaluated [1] resulting in

$$\sigma_\eta^2 \approx E\{|G|^2\}\frac{N_0}{2} = \left[-1 - \left(1 + \frac{1}{\xi}\right)e^{1/\xi}\mathrm{Ei}\left(-\frac{1}{\xi}\right)\right]\frac{N_0}{2}. \quad (18)$$

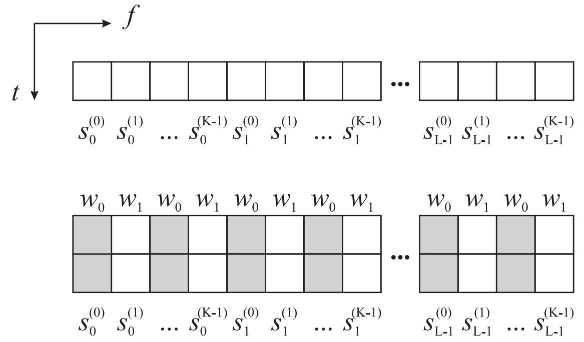

Figure 4: Visualization of the proposed method of block interleaving with additional spreading in time direction.

As ISI β, MAI γ and the noise η are independently Gaussian distributed with zero mean, the sum of all has a zero mean Gaussian distribution with variance equal to the sum of the variances σ_β^2, σ_γ^2, σ_η^2 and the Gaussian approximation can be invoked. Moreover, since the energy E_α of the useful signal part can be assumed to be approximately constant according to [4], the BER calculation using the Gaussian approximation is based on the BER formula for transmission over an AWGN channel

$$P_b = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_\alpha}{2(\sigma_\beta^2 + \sigma_\gamma^2 + \sigma_\eta^2)}}\right). \quad (19)$$

4. Countermeasures to reduce MAI

As discussed in the previous section, user frequency offsets in an SS-MC-MA up-link transmission system cause MAI which lead to an additional performance degradation. In order to develop appropriate countermeasures, the expression for the MAI variance σ_γ^2 given in Equation (16) is investigated in more detail. The MAI variance σ_γ^2 is composed of several terms all weighted by the appropriate ICI coefficient. Taking into account the behavior of the ICI coefficient as described in Equation (10) it becomes clear, that the main contribution to the MAI variance σ_γ^2 stems from terms weighted with either $U_1(\varepsilon)$ or $U_{-1}(\varepsilon)$. These are the ICI coefficients which describe the MAI from neighboring subcarriers. Thus, suppressing the MAI from neighboring subcarriers will lead to a considerable performance improvement. Based on that fact, we propose block interleaving with additional spreading in time direction as countermeasure against MAI in SS-MC-MA up-link transmission systems which works as follows. Instead of transmitting the L chips of the Q BPSK symbols directly, an additional spreading in time direction is introduced as illustrated in Figure 4. Two orthogonal sequences $\mathbf{w}_0$ and $\mathbf{w}_1$ of length 2 are used for this purpose which are chosen to be

$$\mathbf{w}_0 = \left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)^T \text{ and } \mathbf{w}_1 = \left(\frac{1}{\sqrt{2}}, -\frac{1}{\sqrt{2}}\right)^T. \quad (20)$$

Due to the fact, that the spreading sequence $\mathbf{w}_0$ is used for all even and the spreading sequence $\mathbf{w}_1$ for all odd subcarriers, neighboring subcarriers are made orthogonal to each other as long as the coherence time of the

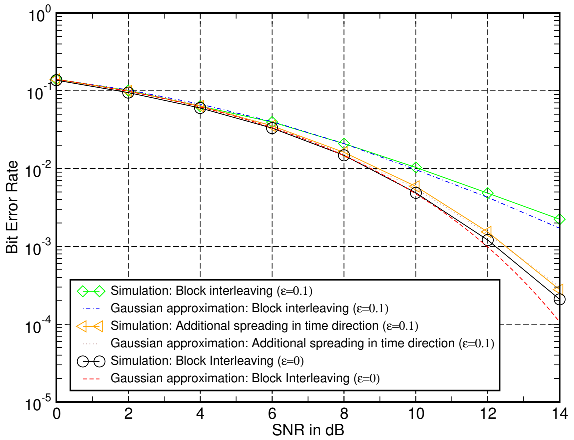

Figure 5: Performance results of SS-MC-MA up-link transmission with and without user frequency offsets for both analytical BER calculations and simulations. Simulation parameters: $K = 32$, $L = 64$, $Q = 64$, and $\varepsilon = 0.1$.

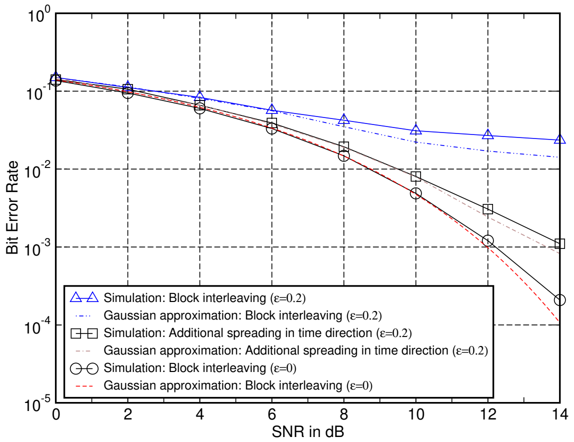

Figure 6: Performance results of SS-MC-MA up-link transmission with and without user frequency offsets for both analytical BER calculations and simulations. Simulation parameters: $K = 32$, $L = 64$, $Q = 64$, and $\varepsilon = 0.2$.

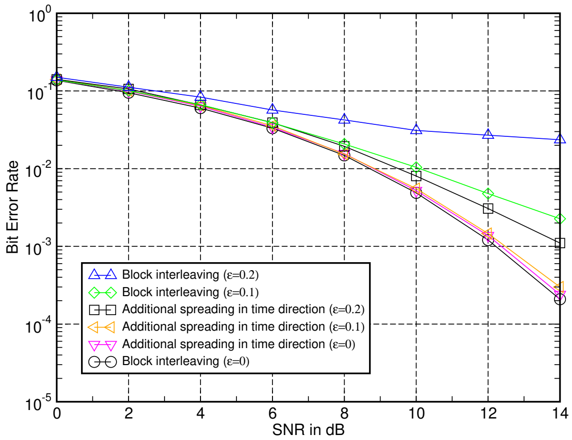

Figure 7: Simulated performance results of SS-MC-MA up-link transmission with and without applying the proposed MAI countermeasure for different user frequency offsets of $\varepsilon = 0.1$ and $\varepsilon = 0.2$. Simulation parameters: $K = 32$, $L = 64$, $Q = 64$.

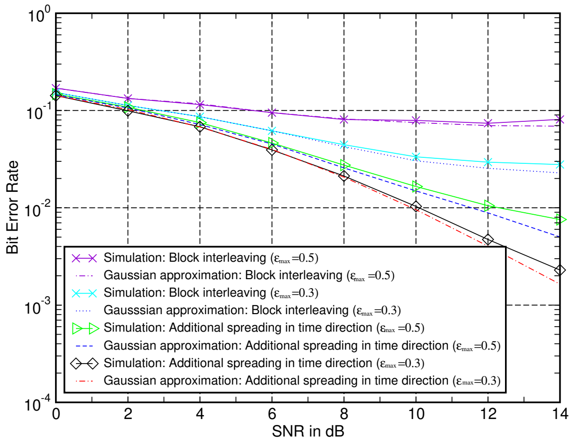

Figure 8: Performance results of SS-MC-MA up-link transmission with frequency offsets for both analytical BER calculations and simulations. Simulation parameters: $K = 32$, $L = 64$, $Q = 64$. Values $\varepsilon^{(k)}$, $k = 0, \ldots, K-1$, are taken from a Jakes distribution.

transmission channel is at least two times the SS-MC-MA symbol duration, i.e. the channel is nearly constant in time direction over the duration of two SS-MC-MA symbols. Since orthogonality is established in time direction, MAI from neighboring subcarriers due to user frequency offsets is avoided. Note, frequency diversity is retained, since this spreading in time direction is combined with block interleaving. The drawback of this scheme is a reduction in transmission capacity by a factor of two.

5. Simulation Results

To prove the validity of the analytical performance evaluation which uses the Gaussian approximation for the BER calculation, simulations for the SS-MC-MA up-link transmission with and without user frequency offsets are performed. In Figure 5 and Figure 6 the analytically obtained BER versus SNR results are compared with the simulation results using parameters $K = 32$, $L = 64$, and $Q = 64$. Both, the simulation results and the theoretical results are obtained for a constant user frequency offset of $\varepsilon = 0.1$ and $\varepsilon = 0.2$, respectively. It can be seen that the analytically obtained results and the simulation results agree very well proving the validity of our approach for the performance evaluation.

In Figure 7 the simulated BER versus SNR results are shown for the proposed MAI countermeasure. Using the same system parameters as previously and two different frequency offsets, $\varepsilon = 0.1$ and $\varepsilon = 0.2$, the performance gains for the proposed MAI countermeasure become visible. As a reference, the simulation results without user frequency offsets are given. From Figure 7 it can be seen, that for $\varepsilon = 0.1$ the performance gain at a BER of about 10^{-3} is almost 4 dB. Moreover, considering user frequency offsets of $\varepsilon = 0.2$ a transmission without the proposed MAI countermeasure is no more possible, since the BER stays above 10^{-2}, whereas applying the proposed MAI countermeasure leads to very promising results.

In Figure 8 the simulation results as well as the theoretical performance calculations for the case where all users have different offsets $\varepsilon^{(k)}$ are shown for $\varepsilon_{\max} = 0.3$ and $\varepsilon_{\max} = 0.5$. It can been seen that the theoretical results agree very well with the simulation results. Moreover, for large values of $\varepsilon_{\max}$ a significant MAI reduction is achieved by block interleaving with additional spreading in time direction.

6. Conclusion and Outlook

The influence of user frequency offsets on the performance of an SS-MC-MA up-link transmission system with MMSE equalization is investigated and an analytical expression for the MAI variance in the case of independent Rayleigh fading is derived. Since it is shown that the MAI is approximately Gaussian distributed, the Gaussian approximation is applied to obtain a closed form solution for the BER calculation. A comparison between the analytical results and simulations prove the validity of the analytical performance evaluation.

Moreover, based on an analysis of the expression for the MAI variance a very promising countermeasure to reduce MAI in the case of user frequency offsets is proposed. Taking into account that the main MAI influence stems from neighboring subcarriers, the MAI influence can be reduced significantly if neighboring subcarriers are made orthogonal to each other. This is achieved by the proposed countermeasure of block interleaving with additional spreading in time direction. The simulation results show considerable improvements which are gained by applying this new MAI countermeasure. Considering user frequency offsets as large as 20% of the subcarrier spacing, SS-MC-MA up-link transmission using the proposed MAI countermeasure is still possible while this is not the case without applying this MAI countermeasure.

The drawback of the proposed MAI countermeasure is that it involves a reduction in transmission capacity by a factor of two. However, the loss in transmission capacity might be compensated by using higher-order modulation schemes with or without combination with trellis coded modulation. Moreover, the MAI countermeasure might be applied in an adaptive manner. That means, only in the case of large frequency offsets which are no longer tolerable, the proposed MAI countermeasure is applied allowing to still transmit with a reduced transmission capacity.

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